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proceedings

AIME-Navy Day Forum

METALLURGY IN THE NAVY

February 15, 1960
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Office of Naval Research
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CONTENTS

PREFACE

This volume contains the complete proceedings of the AIME-Navy Day Forum, "Metallurgy in the Navy," given as part of the annual meeting of the Institute of Metals Division on February 15, 1960, in New York City. The forum was attended by some 600 AIME members and guests who constitute a broad cross section of the metallurgical, industrial, and educational fraternity.

This publication has been compiled under the auspices of the Office of Naval Research to make available to those who have an active interest in Navy problems of research, development, and ultimate procurement of materiel, a record of this authoritative and comprehensive presentation.

Some of the papers included herein have appeared, in whole or in part, in the August and the December (1960) numbers of the Journal of Metals.

The help of all those who contributed to the success of Navy Day is gratefully acknowledged. Much credit is due the officers and members of the Metallurgical Society of the American Institute of Mining, Metallurgical, and Petroleum Engineers for their cooperation in this effort. Finally, the authors are deserving of very special thanks for preparing and presenting their papers and participating in the presentation.

R. E. Wiley

R. E. WILEY
Assistant Research Coordinator
(Materials)
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FOREWORD

The Metallurgical Society Forum on "Metallurgy in the Navy" grew from informal discussions between Society and Navy personnel on the ever-present problem of improving technical communications. In spite of the numerous and expanding channels for oral and written dissemination of technical information, on both materials research and development and on military materials problems, there exists a strong feeling in many quarters that a substantial and important segment of the technical community remains poorly informed on these subjects. This segment is difficult to identify specifically but appears to be primarily related to those individuals and organizations that have, at most, only incidental or remote connections with the Department of Defense, or the Services individually.

It was in the hope of making more intimate contact with the above group and thus enlisting their aid, as well as of reinforcing the lines of communication already established and further clarifying and emphasizing the metallurgical activity and problems of the Department of the Navy, that this Forum was conceived. The concensus of attenders, in retrospect, has judged it to be a very successful experiment and most worthwhile. It will be followed at successive meetings of The Metallurgical Society by similar presentations from the Departments of the Army and the Air Force, thus comprising, in toto, a significant and informative sample of metallurgy and metallurgical problems in the Department of Defense.

N. E. Promisel

N. E. PROMISEL
Bureau of Naval Weapons

KEYNOTE ADDRESS

Howard A. Wilcox

Deputy Director
Defense Research and Engineering

It is a pleasure, privilege, and honor for me to be invited to speak to you today and to underscore the importance of this symposium in relation to the defense of the United States and the Free World. It is transparently clear to us in the Department of Defense, as I know it is to each of you, that every single piece of military hardware is largely determined in its form, structure, and function by the contemporary state of the materials arts and sciences. The energy for the propulsion of all our present military vehicles and weapons comes directly from the transformations of certain material compounds and elements into other material compounds and elements. The functionings of most of our present military payloads depend, at least in part, on the same sources of energy. The electrical, optical, thermal, chemical, biological, and structural properties of materials are all of detailed and vital significance in nearly every one of our defense devices.

The materials research and development business is a fast-moving one. I am tempted to say, for example, that almost no single material part of a modern aircraft has the same basic properties as any single part of an airplane of 20 years ago – you, who are experts in this business, might be able accurately to judge the truth of that sweeping assertion, whereas I can only suspect it to be true. In any case, I think it's sufficiently true to make my point – the materials research and development business is moving fast.

I further suppose that almost none of the materials used by the Defense Department in its military devices is taken raw from nature; nearly all are processed through numerous intricate steps to become substances that are presumably to be found nowhere in the natural universe. The steps taken in fabricating our modern materials depend on the accumulation of man's scientific knowledge and art in the materials field. The race for more knowledge and art in this area is absolutely central to the maintenance of our immediate and long-range defense capability. We cannot afford to slacken our pace in this race.

As a result of this sense of urgency, the Materials Committee of the Federal Council for Science and Technology, and the Materials Advisory Board of the National Research Council, and the Office of the Director of Defense Research and Engineering have been active in a joint review of our national position in the various phases of the materials sciences and arts. By way of proving our earnestness, the Department of Defense has made $20 million available from the FY 1959 Emergency Fund to accelerate development of new materials. Moreover, the Department of Defense is, through the Advanced Research Projects Agency, making $14 million available in FY 1960 for the creation in some of this country's universities of "interdisciplinary materials laboratories." These laboratories are predicated on the ideas that chemists, physicists, mathematicians, and other kinds of scientists can make more effective attacks on materials research and development problems by working closely together, and that such laboratories can also do much to raise our national rate of education of scientists in the crucially important materials areas.

Of course, the nation's whole materials research and development program is vast indeed. I would estimate that industry, the academic laboratories, and the Government laboratories devoted a total effort to this area amounting to perhaps $1 billion in FY 1959. Thus, it is easy to see that the augmentation funds I mentioned earlier really represent a rather small percentage increase in the total effort. We hope, however, to make the impact of this augmentation significant, out of proportion to its magnitude, by careful cultivation of the interdisciplinary laboratory idea.

KEYNOTE ADDRESS

There always seems to be a feeling in some circles that a large and multifaceted effort like the national materials research and development program is almost automatically shot through with extensive undesirable duplication of effort. Maybe so. But I for one suspect that this feeling represents a bureaucratic management viewpoint engendered by the extensive and heavily ramified operations of that very bureaucracy. I believe that a large and multifarious scientific effort is actually self-policing, provided that the managers let the knowledgeable and responsible investigators choose their own lines of activity, and provided an adequate information exchange is fostered. In this case I would think that some duplication of effort appears to occur, and does occur, and needs to occur, but this is more accurately described as alternative approaches and needed cross-checking. I would deny that undesirable duplication occurs to any significant extent.

If the foregoing view is correct, it points up the vital role in the information exchange program that is played by this symposium. The host society represents a good cross section of the finest scientific knowledge and ability available in this country. Moreover, its membership constitutes a research and development base far broader than that which is now directing its efforts toward solution of our military material problems in Government laboratories and programmed research areas. Therefore, this symposium will provide a very significant liaison forum for the exchange of information and, by stimulating an increased rate of advance in materials knowledge pertaining to the problems of the Department of Defense, will make a very direct contribution to the welfare and security of the Nation and the Free World.

INTRODUCTORY REMARKS

Honorable James H. Wakelin, Jr.

Assistant Secretary of the Navy for Research and Development

I am happy to have the opportunity to address a few brief remarks to the Metallurgical Society of the AIME. I want to assure you that I am not here simply as a disinterested observer. We in the Navy need the assistance of each and every one of you to help solve the research and development problems of the Navy of the future in the materials area. I have come here to urge you personally to mobilize your know-how, your inventiveness, and your scientific facilities and laboratories to give us the push we need to break through the barriers ahead of us.

When we in Navy research and development speak of the Navy of the future, we are not merely thinking about the advanced ship types, aircraft, and missiles now in production or in the final design stages, but rather about the fleet of the period 10 to 15 years from now. At the present time we have many broad plans for the Navy of the future, but technology is advancing so rapidly that it is very difficult to be sure we have guessed correctly.

The rapid march of progress during the past 10 to 15 years has added a new twist to the delicate problem of predicting the future. It seems that no matter how wildly we may use our imagination to look into the future, we usually are much too conservative in our estimates, judging from our performance in the recent past.

In the years before World War II, man's imagination seems to have been stifled, especially in this country. The crisis of World War II brought about a change in this human quality, but we are still in the learning stage as far as really effective use of our imagination is concerned. The military now depends on people who have the ability and the aggressiveness to attempt to find unusual and daring solutions to its problems. This is the only way the United States can stay ahead in our race for scientific supremacy which, in plain terms, means national survival.

The Navy is fortunate to have always had a few men in key positions of authority who could not only foresee the future of the Navy but also could boldly provide the extra shove to help get us started in the right direction. In 1939, for example, the Navy was informed by Dr. Enrico Fermi that scientists had succeeded in splitting the uranium atom, releasing tremendous energy for potential application. The practical problem of harnessing this energy had yet to be solved. Nevertheless, a Navy administrator, who happened to be the Chief of the old Bureau of Engineering, approved the expenditure of funds for a research program aimed at utilizing this new source of power for ship propulsion. Less than 16 years later, in spite of the war time emphasis on developing the atomic bomb, the Navy's submarine NAUTILUS, the world's first nuclear powered ship, was operating successfully.

Near the end of the war, the need for continuous military-supported research became apparent in order to provide the basic scientific knowledge required for new fields of development. In 1945, Secretary of the Navy Forrestal issued a directive establishing the first military agency specifically designed to support scientific research on a continuing basis at universities and laboratories throughout the country. In 1946, Congress confirmed his judgment by establishing this organization as the Office of Naval Research.

In 1946, there was very little serious thought being given to the concept of ship-launched long-range missiles. Yet, in 1947, Admiral Chester W. Nimitz in a special report to the Secretary of the Navy stated: "In addition to the weapons of World War II, the Navy of the future will be capable of launching missiles from surface vessels and submarines... ." He also warned that in the event of war within the next decade our early combat operations must be aimed at protecting our vital centers from devastating attacks by missile-launching submarines. Today, the Navy is in the process of building a whole fleet of guided and ballistic missile ships and submarines, and is developing specialized ASW task forces which are trained and equipped to hunt and kill enemy submarines armed with long-range missiles which may threaten our coastal cities.

INTRODUCTORY REMARKS

The Navy is uniquely organized to exploit the latest advances in science and technology with its decentralized research and development organization. In contrast to a general staff type of organization, the Navy carries the principle of delegation of authority and decentralization of responsibility to the lowest level possible consistent with efficient and business-like operations. The principle of decentralization can be readily seen not only in the organization of the Navy Department as a whole but in the organization of fleets, the bureaus, the laboratories, field activities, and, in fact, the entire shore establishment of the Navy.

The organization of the Navy Department is bilinear in that two lines of authority extend downward from the Secretary of the Navy. One line extends through the Chief of Naval Operations to the operating forces of the Navy, representing the military element of the Navy Department. The other line runs from the civilian assistant secretaries to the technical bureaus and offices and to the shore establishment and represents the business elements of the Navy. These two elements are integrated through constant liaison and coordination at all levels.

Furthermore, the Navy frequently reviews its organization to determine if certain portions of our operation have become obsolescent as a result of changing times. The most recent study was made by a board headed by William Franke, who was appointed Secretary of the Navy shortly after his report was published. About five years ago another study of Navy organization was made by a board headed by Thomas Gates, who later became Secretary of the Navy. This pattern indicates that in the Navy when a man signs his name to recommendations for changes, he is likely to end up with the job of carrying them out.

One recommendation by the Franke Board led to the amalgamation of the Bureaus of Ordnance and Aeronautics into the Bureau of Naval Weapons, which now conducts approximately two-thirds of the total development effort of the Navy. By this change, certain areas of split cognizance were eliminated, especially in the problems of missile research and development.

Another recommendation of the Franke Board was the establishment of the position of Assistant Secretary of the Navy for Research and Development, which I now hold. I am responsible for policy, management, and control of Navy Department research, development, test, and evaluation matters, including general management of the appropriation RDT&E,N. My advisor on research matters is the Chief of Naval Research, Rear Admiral Rawson Bennett, who will speak to you later today about his functions. Briefly, he heads the Office of Naval Research and has the responsibility for coordinating and integrating, in collaboration with the other bureaus and offices, the research programs of the Navy.

Another key position in the research and development organization of the Navy, which was also established as a result of the recommendations of the Franke Board, is the Deputy Chief of Naval Operations for Development. Vice Admiral Hayward has been selected to fill this job. He is responsible for the coordination and integration of the Navy's research and development program for the Chief of Naval Operations and issues operational requirements for new weapons and equipments.

In general, the development of the new equipment will require that some increment of basic or applied research be completed. If we are lucky, or have planned carefully, most of this basic or applied research will have been completed - or at least be in progress - before the operational requirement for the new equipment is issued.

Basic research in the Navy is primarily the responsibility of the Office of Naval Research, although each of the bureaus and offices carries on a small portion of the total basic research effort either in their own laboratories or through contracts with industry or educational institutions. Applied research and development is conducted primarily by the bureaus, and to a small extent by ONR, in response to the requirements of the Chief of Naval Operations. This program is coordinated by the new Deputy Chief of Naval Operations for Development and integrated into the overall Navy RDT&E program.

Design and development is carried out by the Bureaus either by contract to industry or by Navy laboratories or field activities. Once the hardware is available, a test and evaluation program is initiated to insure that the product which has been developed is satisfactory and suitable for fleet use. The elapsed time between the point where the basic research, which made this development possible, was begun and the point of final acceptance for fleet use may be as little as five years but more likely may be as much as 10 to 15 years.

INTRODUCTORY REMARKS

It is essential, therefore, that our research and development planning be effective and complete. For example, the Navy's Long Range Objectives, which are revised each year, cover a time span of approximately 15 years into the future. They are based on the predicted threat in the future, trends in national policy, and the predicted state of the technical arts. The current publication covers the period from 1969 to 1974. The implication of these objectives, in terms of required research and development, is spelled out in the document. In turn, the principal procurement bureaus – the Bureau of Naval Weapons and the Bureau of Ships – in their own Long Range R&D Plans attempt to predict the hardware which can be developed in the future, based on estimated technological advances in the interim.

But, as Shakespeare has said, there's the rub. How far can we go in planning new weapons and equipment which require materials that do not exist at the time the plans were made? Advances in metallurgy and other material fields are a critical factor in the ultimate realization of our research and development plans. It is imperative that research and development progress in materials stay well ahead of our current requirements if we are to progress rapidly and orderly with new weapons for the Navy of the future. This requires that the scientific community be made fully aware of the future needs of the Navy and the other services in the field of new materials.

Today you will be told of the Navy's needs for research and development in materials. It will become apparent to you that our Fleet utilizes just about every type of weapon and equipment in the national arsenal. We operate on the sea, under the sea, in the air, and on land with our amphibious operations. You will see that our research and development program is almost as broad and diversified as science and technology itself.

The Metallurgical Society of the AIME represents an excellent cross section of the finest metallurgical knowledge and ability available in this country. Not all of your members, however, work on military material problems through government sponsored research programs in universities and laboratories. Some have had no previous contact with the Navy.

We hope that through the medium of this symposium, you and your colleagues will gain a clearer understanding of what the Navy plans and hopes to accomplish and how you can help us reach these objectives. We also hope that you will be stimulated to bring to our attention new developments or new methods of approach to the solution of metallurgical problems which are not now being exploited.

You are the experts, and we need your advice and guidance. The challenge is one of the greatest magnitude. On the other hand, no less than the security of our nation is at stake. The responsibility for maintaining our defense against whatever fantastic forces may threaten us in the distant future cannot be borne alone by the Navy or the Department of Defense, but must be carried on the shoulders of all who can help to share the load.

CHAIRMAN'S INTRODUCTION TO TECHNICAL SESSIONS

N. E. Promisel

Bureau of Naval Weapons

Today's technical program, as you will have noted, is divided into not only two sessions but also into two major categories. The first deals with certain weapons, systems, applications and, in general, end-items of importance to the Department of the Navy and, therefore, of importance to our national defense posture. In many respects, also, these end-items comprise an important contribution to industry and to our national peacetime welfare. Obviously, they represent only a very small portion of the Navy's broad interests, which have already been indicated to you by Secretary Wakelin, but they have been selected for discussion because successful achievement in these fields is vitally dependent on the solution to many materials problems, and because they illustrate materials problems running the gamut from solid-state physics to fabrication operations, from cryogenic temperatures to temperatures in the neighborhood of the melting points of our highest melting materials, with special requirements challenging our most sophisticated understanding of the flow, fracture, physical, and chemical behavior of metals, ceramics, and materials, generally. By no means are the three areas which we have selected for discussion unique in this respect. I assure you that it was a real problem to limit ourselves to only three subjects.

We hope that after you have heard these three presentations you will have a "feel" for some of the metallurgical problems which confront us. The translation of weapon and system design and requirements into material problems is rarely simple. It is relatively easy to deduce the superficial and more obvious material requirements, such as yield strength. The more subtle, and often overriding, requirements are much more difficult to define, certainly in quantitative terms. For example, how does one specify, realistically, minimum ductile behavior in a critical application? Unfortunately, sometimes the answers are forthcoming only after extensive, preliminary, quasi-service-type tests, and sometimes, not even then. "How to test" is itself a profound materials problem. Nevertheless, the speakers will aspire to emphasize and define materials problems to the maximum degree practicable, and to the specific parameters which will be spelled out here one must always add the supplementary, but by no means unimportant, considerations such as cost, producibility, availability, reliability, maintainability, etc.

With this type of exposition as background, in the afternoon we shall describe briefly to you the overall Navy program and philosophy in metallurgy and describe some highlights of Navy research and development in five specific areas. Again, these few areas are merely touch-points, selected in part to represent diversity. In part, they relate intimately to the systems described this morning. In part, they illustrate the two facets of the Navy philosophy in materials research and development: on the one hand, to be devoted to solving the problems which our weapon and end-item designs create; on the other hand, to be independent of the immediate, specifically identifiable problems, and to create a reservoir of understanding and knowledge and a spectrum of materials from which we can draw, without the time penalty of having to start from scratch when the inevitable "unexpected" requirement arises. It is in this context that some of our afternoon's discussion will be presented.

The previous speakers have very eloquently and pointedly emphasized the impressive role which materials creativity plays in the success of our many missions. The significance of the improved communications we hope to achieve by meetings such as this is apparent, and we solicit your comments, suggestions, and discussion, not only in today's sessions but afterwards as well.

METALLURGICAL MATERIALS PROBLEMS ASSOCIATED WITH DEEP-DIVING SUBMARINES

CAPT T. B. Owen, USN, and G. Sorkin

Bureau of Ships

* * * * *

ABSTRACT

The need for deep-diving military submarines and the feasibility of their construction from the viewpoint of structural design and materials capabilities are presented. The technical problems encountered in design and construction of the hull are outlined and the properties of some metals and alloys in relation to these problems are discussed. Some areas in metals and their fabrication, in which new developments are required, are indicated.

* * * * *

INTRODUCTION

We have chosen to discuss certain problems associated with deep-diving submarines this morning as being indicative of the challenges that face the metallurgical community in supporting the ever-increasing demands of a fast-moving, military technology. Since time does not permit a complete coverage of all the difficulties that we encounter, I will concentrate primarily on the fundamental question of the selection of hull structural materials and the properties they must possess if they are to be useful in naval submarine construction and operation.

BACKGROUND

History

The desires of the navies of the world to capitalize on the tactics of stealth and surprise in the conduct of operations have led them to an ever-increasing exploitation of the dreams of Bushnell and the crude submersible of Holland (Fig. 1). At the start of World War II, submarines had been developed that could cruise on the surface at high speeds over long ranges under diesel power. They could dive to 300 feet and cruise at greatly reduced speeds for as long as 36 hours on battery power, until the need for air and battery power replenishment required them to surface. One might say that these were surface ships capable of submerging. Their capabilities, however, permitted them to account for tremendous tonnages of merchant shipping.

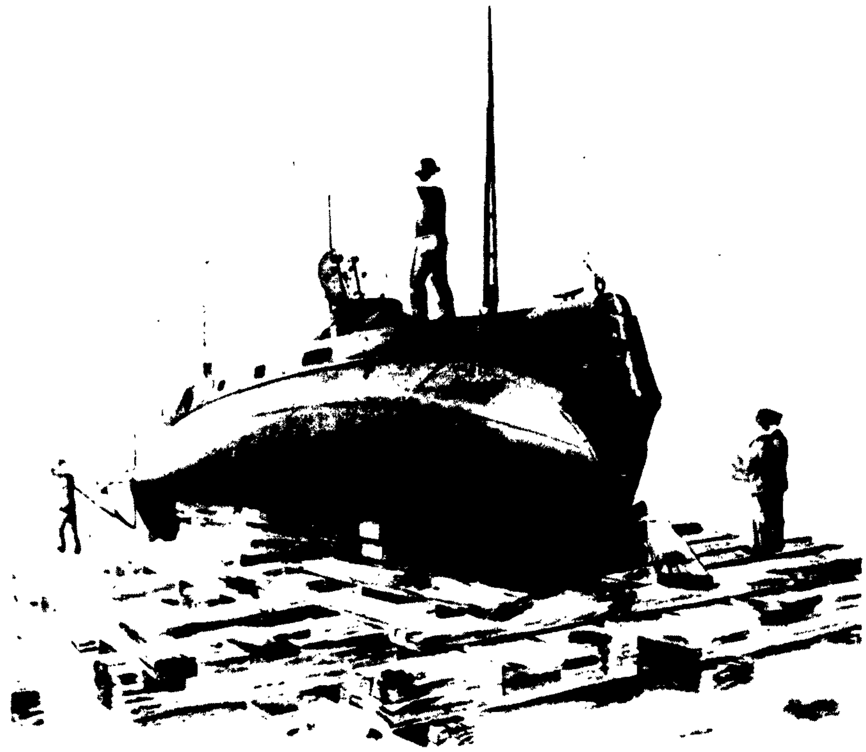

Fig. 1 - USS HOLLAND, an early crude submersible

Current Trends

With the advent of nuclear weapons, the promises of nuclear power, and the installation of the snorkel device at the close of the war, the Navy realized that the potentialities of the submarine would continue to grow and should be fully exploited. Radar and sonar developments required that the underwater ships of the future be capable of prolonged submergence and high underwater speeds. In 1946, the Navy started its serious effort to develop a nuclear power plant for marine use. At the same time it took a good look at the hull configuration of conventional submarines. Those used in World War II were long and narrow. This configuration permitted high-surface speeds but offered only marginal performance under the water.

The two parallel development efforts came to fruition at about the same time. The former culminated in the first real application of nuclear power – the NAUTILUS (Fig. 2) – and made it possible for man to cruise beneath the surface of the sea for extended periods. Hydrodynamic studies of hull shapes led to the whale-like design used in the submarine ALBACORE (Fig. 3) built to give high underwater speeds. At last, the Navy had the combination of design and power plant that could now be exploited in producing the submarine of the 1960-1970 era – a true submersible. Developments in structural materials also permitted operations at greater depths.

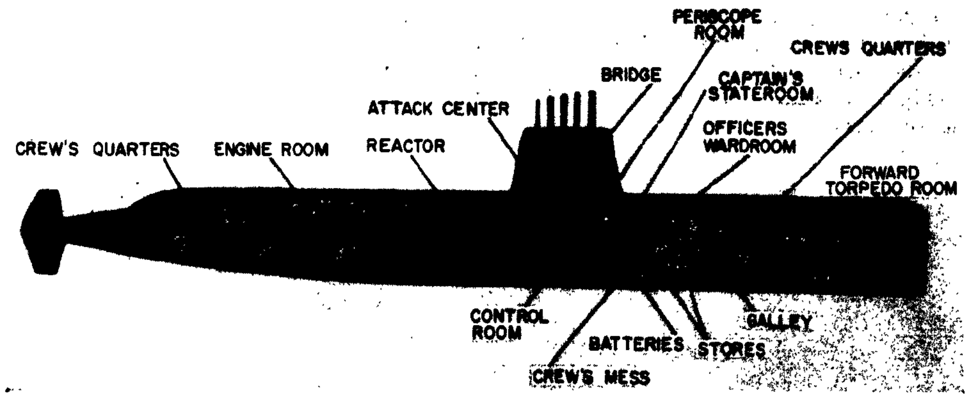

Fig. 2 - USS NAUTILUS, first nuclear-powered submarine

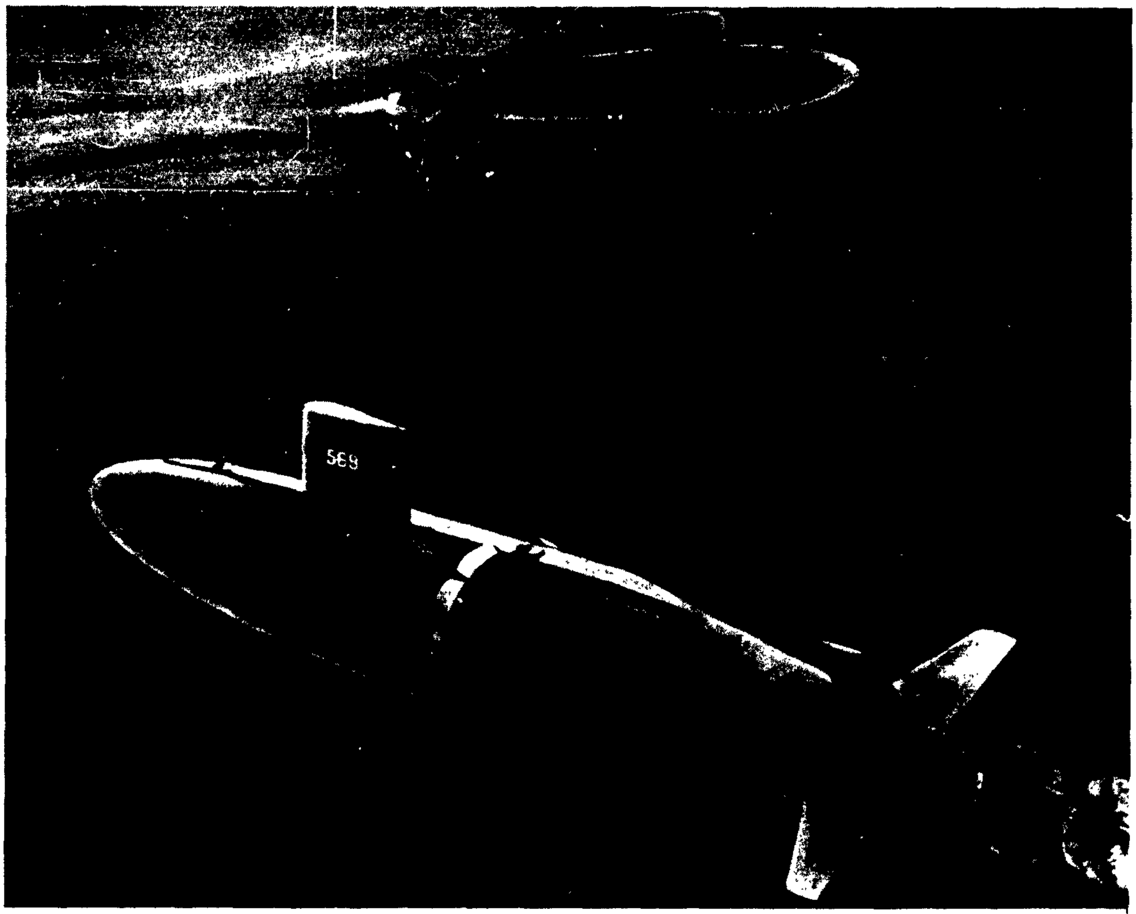

Fig. 3 - USS ALBACORE, whale-like design model

These developments have lead to the design and construction programs for two types of underwater ships – the attack submarine (Fig. 4) and the Fleet Ballistic Missile submarine (Fig. 5) – each with a definite mission. The former has the task of locating and destroying all types of ships. The latter is the well-publicized strategic deterrent – the POLARIS missile-launching submarine.

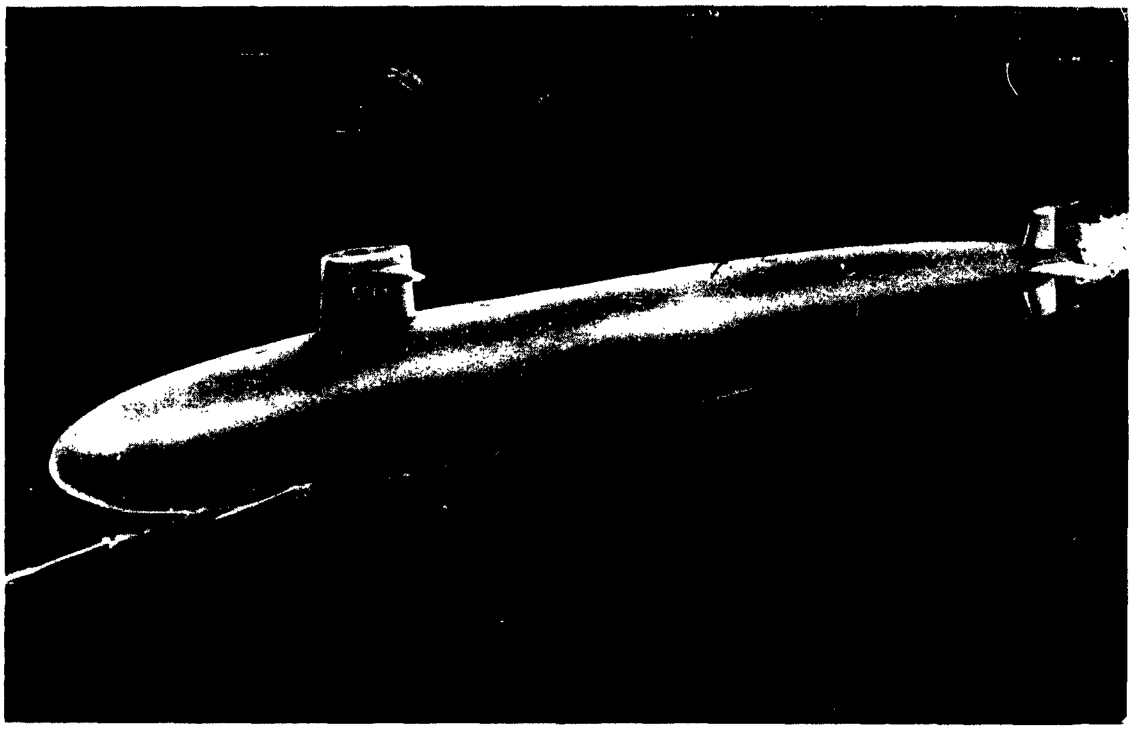

Fig. 4 - Attack submarine

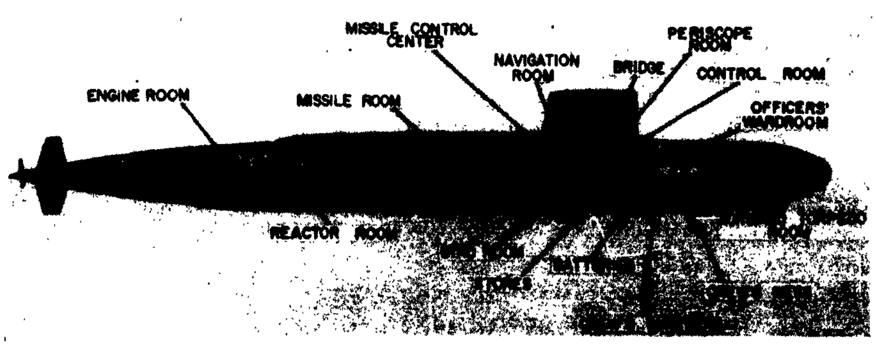

Fig. 5 - Fleet Ballistic Missile submarine

Collapse of Time

These developments are illustrative of the increasing pace of technological advancement that we see in every phase of science and engineering (Fig. 6). The exponential rise in our capabilities is, of course, accompanied by a similar increase in the severity of military requirements that must be met if we are to have the offensive and defensive means for maintaining national security. Submarine design must keep pace with these developments.

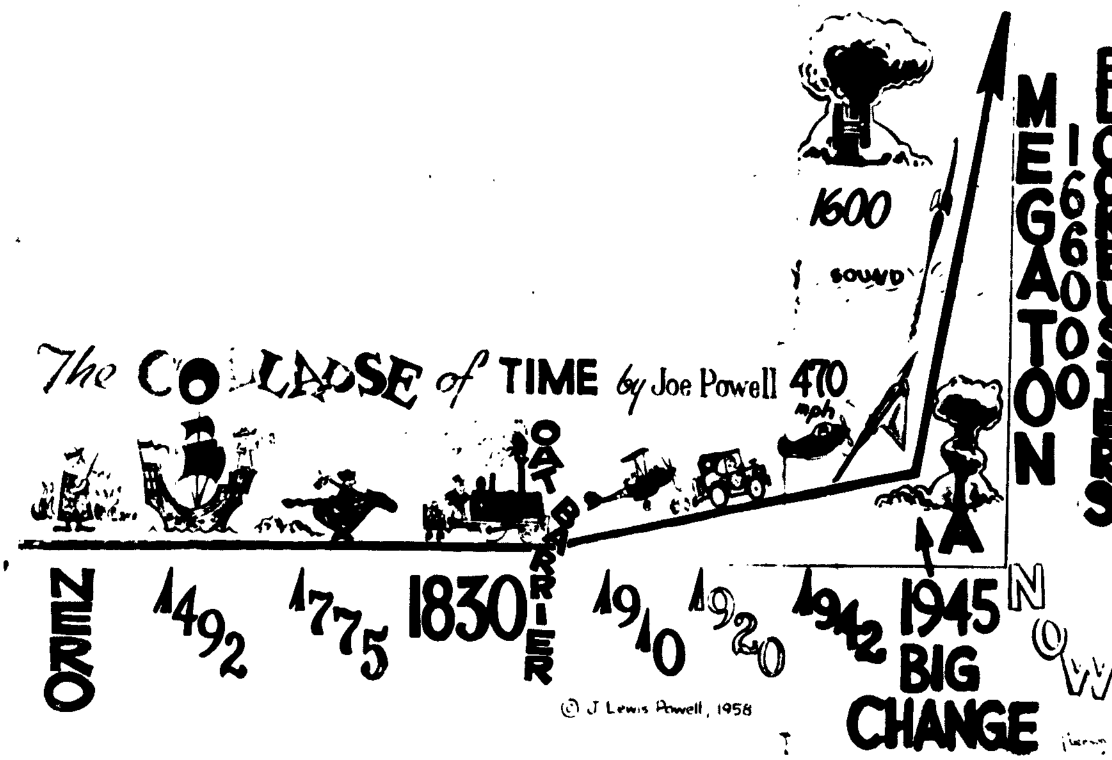

Fig. 6 - The collapse of time

Need for Depth

Modern submarine development and operation calls not only for the ability to remain submerged for long periods of time but leads to the requirement for increased operating depths. Just as aircraft have capitalized on altitude so must we go deeper to gain the greater freedom of movement offered for both offensive and defensive tactics. Not only will we gain in stealth and surprise but we will be able to take advantage of the enhanced sonar properties of the oceans at these depths. An added benefit accrues from the fact that a ship built to withstand greater pressures will have greater resistance to attack at shallower depths because of larger reserve strengths in the hull.

MATERIAL

The current hull structural material is a high-strength, low-carbon, quenched and tempered martensitic steel with a nominal yield strength of 80,000 psi (Fig. 7). The alloy is the result of many years of experience and is considered the best available today for the intended use. Its analysis is shown on the figure. In the design and construction of our present submarines we are squeezing every last bit of capability that this particular material offers. Extreme care is required throughout the whole fabrication process to insure structural integrity under operational conditions.

If we are to attain "order of magnitude" increases in depth we must examine, from a design and performance standpoint, a whole series of metals and alloys to establish the direction that research and development in hull structural material must take.

PLATE GAUGE, IN	CARBON %	MANGANESE %	SILICON %	CHROMIUM %	NICKEL %	MOLYBDENUM %
UP TO 1-1/4 INCL.	.22 MAX	.10/.40	.15/.35	.90/1.40	2.00/2.75	.23/.35
OVER 1-1/4	.23 MAX	.10/.40	.15/.35	1.35/1.85	2.50/3.25	.30/.60

	YIELD STRENGTH 0.2% OFFSET KPSI	TENSILE STRENGTH KPSI	ELONG. % IN 2"	RED IN AREA %	CHARPY "V" NOTCH FT. LBS AT -120° F (LONGITUDINAL)
1/2	88/89	103/104	25	67/75	123 ± 30
1	86/88	103/105	23	67/74	105 ± 36
1-1/2	87/89	106/107	24	65/74	113 ± 42
2	88/89	106/108	23	66/73	90 ± 30

NIL DUCTILITY TEMPERATURE: -130/-150° F BASED ON
NRL DROP WEIGHT TEST

Fig. 7 - Chemical composition and typical mechanical property range

Design Considerations

Modes of Failure - For submarine structure designed to withstand hydrostatic pressure, consideration must be given to all possible modes of failure. These modes are shown in Fig. 8. Because the design procedure necessary for establishing feasibility can be concerned only with the basic stiffened cylindrical portion of the hull, only three modes of failure need be considered

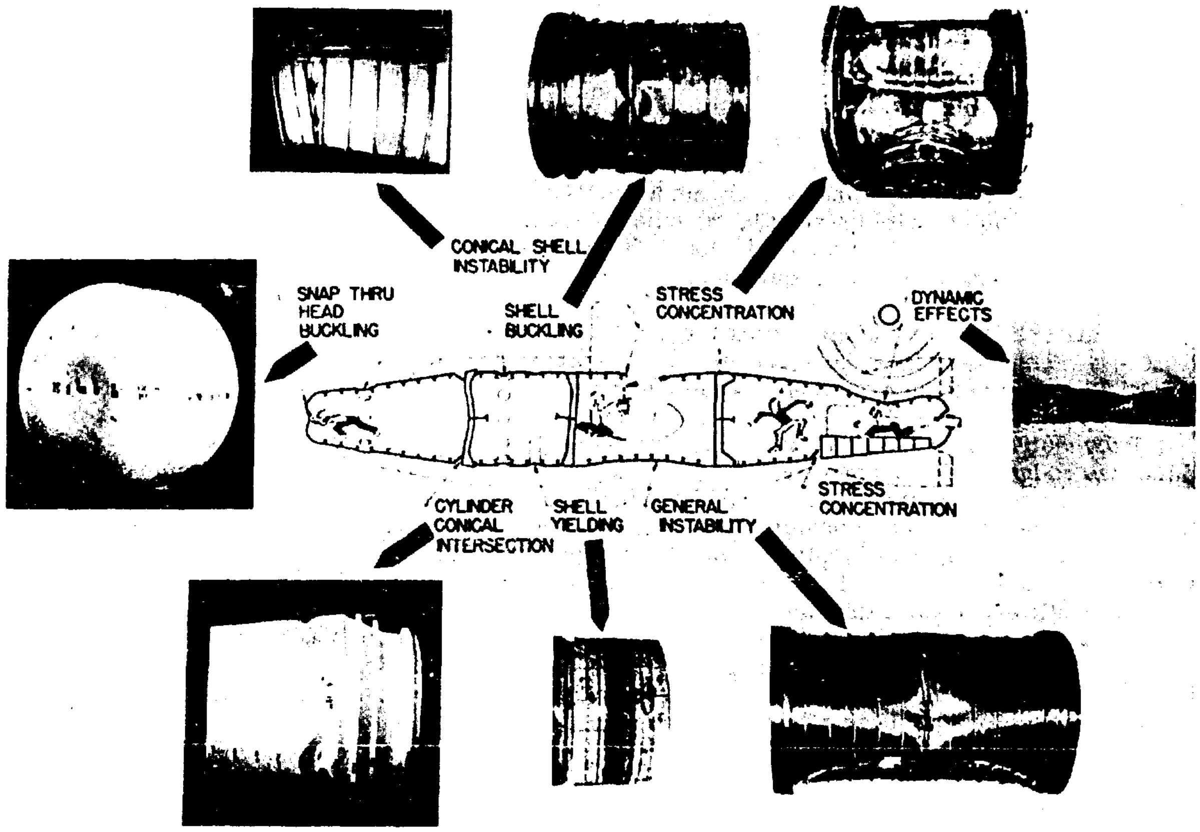

Fig. 8 - Possible modes metal of failure due to hydrostatic pressure

1. Shell buckling: The formation of asymmetric lobes in the shell between frames;

2. General instability: Overall collapse of frames and shell together between bulkheads; and

3. Shell yield: The formation of an axisymmetric pleat in the shell between frames.

A hull which fails by shell buckling is not normally of efficient design because:

(a) Just as for the buckling of a column, the failure is one of instability, i.e., failure before the yield strength of the material is reached because of improper proportions of structure in relation to the modulus of elasticity of the material, and

(b) Again as for the buckling of a column, the structure is markedly susceptible to imperfections. It is prudent to note that, although the mathematics involved in analysis are almost always predicated on perfect geometry, practical construction almost always contains initial imperfections.

Similarly, a hull which fails by general instability is not normally of efficient design and for the same general reasons as for shell buckling -- improper proportions and susceptibility to imperfections.

Conversely, a hull which fails by yielding of the shell is of efficient design because the material has been worked to its yield strength. Therefore, the design procedure used here is based on assuring failure by shell yield.

Initial Selection Criteria - With the design procedures and geometric restrictions used in submarine construction, one can examine a variety of materials under conditions of varying shell thickness, frame spacing, and frame area. Three properties of material alone are considered at this point: yield strength, modulus of elasticity, and specific weight – the last because hull weight must be a small enough fraction of displacement to permit a military payload and necessary propulsion equipment.

No material is ideal in satisfying the combined requirements of strength, stiffness, and lightness. There are four, however, which show promise: beryllium, aluminum, titanium, and steel. These have been examined in some detail.

Procedure - For each material, several shell thicknesses (actually the ratio h/R of shell thickness to hull radius) were chosen. For each shell thickness all possible combinations of frame spacings and frame areas were investigated. In turn, the collapse pressures in each of the three modes of failure considered were computed for each combination as were the ratios of hull weight to weight of displacement. This then led to the most efficient (that is, the least weight) design for each shell thickness. By following this procedure, the most efficient designs for fifteen different shell thicknesses for each of seven materials (four different strength levels for steel) were determined. These are shown in Fig. 9. Figure 10 shows the relation between collapse depth and the ratio of shell thickness to hull radius for the several materials. This involved evaluation of more than 10,000 specific designs. Needless to say, this type of study could not possibly have been attempted without a high-speed computer.

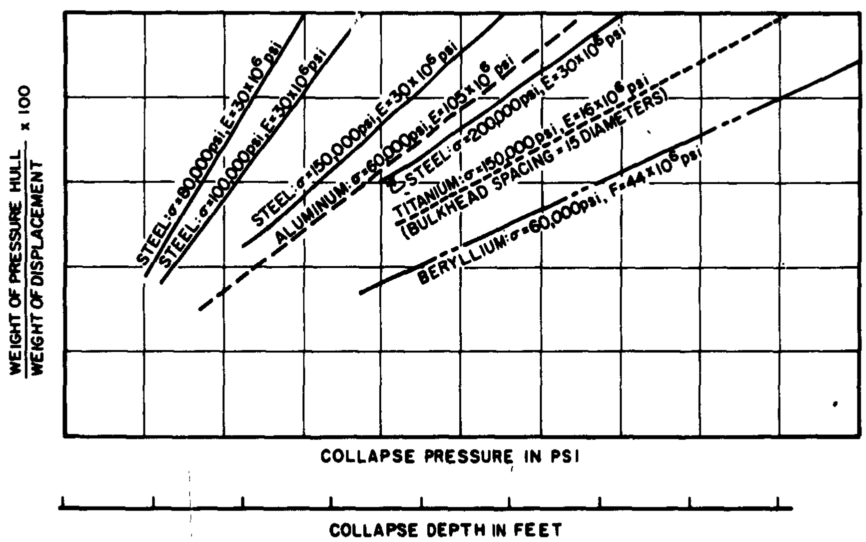

Fig. 9 - Least weight versus collapse pressure for fifteen shell thicknesses for each of seven materials (the ordinate and abscissa magnitudes have been omitted for security reasons)

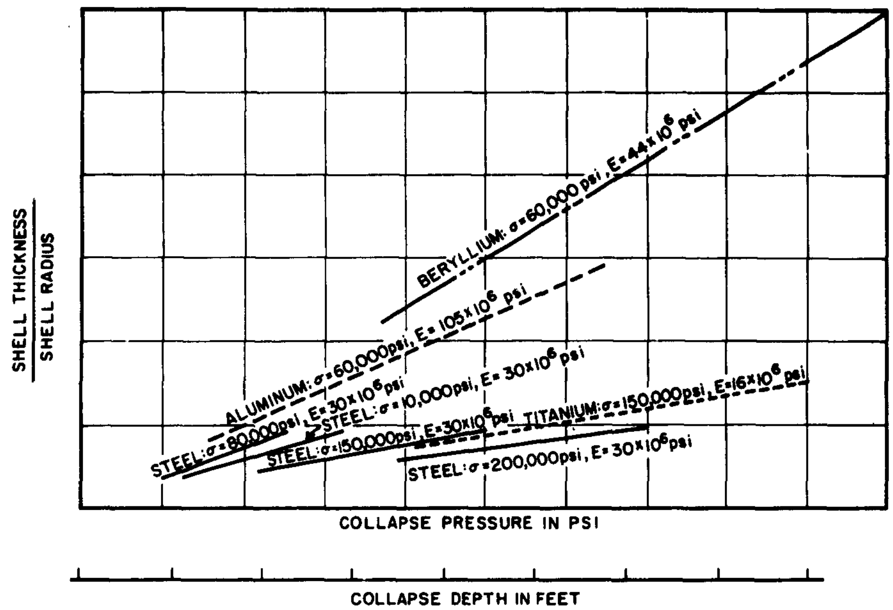

Fig. 10 - Ratio of shell thickness to hull radius versus collapse pressure for seven materials (the ordinate and abscissa magnitudes have been omitted for security reasons)

Summary - It is wise to pause at this juncture and contemplate what has not been considered as well as what has been included. Only hydrostatic pressure has been used as a design load. Only stiffened cylinders have been considered. Existing theories and analyses which have been verified experimentally have been used for design. Geometrical restrictions currently in use have been followed. Nothing new in the way of structural disposition or geometric configuration has been involved. Only specific weight, yield strength, and modulus of elasticity of the materials have been taken into account. No account of such important material properties as impact strength, ductility, notch toughness, corrosion resistance, energy absorption, fatigue, or weldability has been taken. In short, existing design procedures have been applied to different materials which, on the basis of strength, stiffness, and lightness, seem to have promise. Moreover, certain design considerations of great importance to the eventual success of the deep-diving submarine such as closures, noise, machinery, propulsion, sonar, habitability, etc., were not considered.

The results of the feasibility study indicate that we can build a deep-diving submarine provided the material selected on the basis of strength, stiffness, and density meets all the many other criteria mentioned above, and the design problems also mentioned above can be resolved.

Technical Problems

Complexity - Study of the two sets of curves just shown points up two major areas for consideration.

(a) The alloys which appear to be best suited for the deep-diving submarine on the basis of strength, stiffness, and lightness are ones with which we have had the least experience in the sizes and under the conditions we need to use them; and

(b) Major research efforts are needed before any of these potentially useful alloys can be specified for a submarine. Beryllium, which appears to answer the bill more than other alloy studied, is scarce, expensive, and difficult to fabricate. It has never been produced in anywhere near the sizes needed. Tremendous amounts of data are available on titanium alloys, but who has welded heavy titanium plate or studied its notch toughness under explosive loading? How will we weld 60,000-psi aluminum or 150,000-psi steel in heavy sections?

Parameters Due to Loading - Design and material are interdependent since the former depends on the capabilities of the latter. Mechanical properties, other than compression yield strength as determined from the tensile test, with which we are most concerned are creep, notch toughness, and static and plastic fatigue strength. It is difficult to divorce the properties of joints (butt and fillet welds) from all these considerations, but in order to have a reference for discussion let us consider first just the base metal.

(a) Notch toughness (dynamic-loading parameter): In selecting construction materials the Navy has placed considerable emphasis on tests which will evaluate the behavior of the alloy's resistance to fracture in the presence of sharp notches under high rates of loading. High rates of loading, low temperatures, and stress concentrations increase the probability of brittle fracture in steels. For submarines it is mandatory that these structures not fail by brittle fracture when it is deformed over a large area such as by depth charge explosion.

(b) Fatigue (dynamic-loading parameter): In the past this has not been of great concern in submarine hulls. With greater stresses and cycles due to deeper and more frequent dives, this phenomenon becomes extremely important. In the design of submarines there are certain portions of the structure where the stress resulting from deep dives approaches the yield strength of the material. The concern then arises as to the number of cycles that can be experienced before failure under plastic strain fatigue. At present there is uncertainty as to the behavior of various alloys under these conditions. In order to increase reliability of data, large specimens and simulated structures must be tested. The role of residual stresses in the fatigue of structures has never been well evaluated. Since the residual stresses are tensile, and loading of the structure in diving is essentially compression, we will constantly be loading the structure from tension to compression.

(c) Creep (static-loading parameter): Room temperature creep as exhibited by certain titanium alloys may be of concern if dimensions change sufficiently to alter critical volume considerations.

Fabrication Considerations - Structural shapes are currently made up of welded sections. This procedure is expensive and time consuming, and it involves the usual difficulties connected with welding.

(a) Forming: The ideal submarine hull will have a minimum of welded joints. One step in this direction would be the forming of pressure hull plating with integral framing. The usefulness of extruded shapes, regardless of alloy, is apparent. Novel design concepts, some of which are based on extrusions, have been studied extensively.

The stronger materials and larger masses required for new designs indicate that hot forming of massive structures with subsequent heat treatment would be desirable. This is beyond the capabilities of most shipyards but can be done by the steel producers. A metallurgical advantage could be gained wherein the distribution of stresses in the metal would be more favorable than those resulting from cold-forming practices.

(b) Welding: Current plate material is a high-strength, quenched and tempered Ni-Cr-Mo steel designated as HY80. It is sensitive to fabrication parameters. Close control of the welding operation is required if crack free welds are to be produced. The cracks experienced are attributed to high restraints, welding techniques and procedures, joint preparation, and metallurgical factors such as stresses resulting from phase transformation and stress concentrations at sites of inclusions, segregations, and laminations. Basic guidelines for the welding of the material have been promulgated to show the close control required for successful fabrication. The use of higher strength steels depends on solving welding problems associated with the materials.

(c) Other joining methods: Unusual methods of joining, such as shrink fits and organic adhesives, must be considered, particularly if it is found that the alloys are not joinable by other means at the strength levels we are interested in.

Assessment of Materials

(a) Beryllium: Because of its scarcity, cost, and difficulty of fabrication, serious consideration of beryllium as a hull structural material will not be pursued at this time (Fig. 11). We are, however, studying its marine corrosion characteristics under stagnant and high-velocity sea-water conditions and are watching developmental efforts sponsored by other agencies of the government.

	HY 80 STEEL	HY 150 STEEL	HY 200 STEEL	BERYLLIUM 60,000	ALUMINUM 60,000	TITANIUM 150,000
CURRENT AVAILABILITY IN HEAVY SECTIONS	GOOD	POOR	POOR	POOR	FAIR	FAIR
COST	LOW	LOW	LOW	HIGH	LOW	HIGH
FABRICABILITY	GOOD	QUESTION	QUESTION	POOR	FAIR	QUESTION
WELDABILITY OF HEAVY SECTIONS	GOOD	QUESTION	QUESTION	POOR	POOR	QUESTION
CORROSION RESISTANCE	POOR	POOR	POOR	QUESTION	FAIR	EXCELLENT
NOTCH TOUGHNESS	EXCELLENT	QUESTION	QUESTION	QUESTION	QUESTION	QUESTION
CREEP RESISTANCE	GOOD	GOOD	GOOD	QUESTION	GOOD	QUESTION
DENSITY, LB/CU IN.	.28	.28	.28	.066	.10	.16
ELASTIC MODULUS PSI	30×10^6	30×10^6	30×10^6	44×10^6	10.5×10^6	16×10^6
COMPRESSIVE YIELD STRENGTH KPSI	80	150	200	60	60	150

Fig. 11 - Material assessment for a deep-diving submarine

(b) Aluminum: In Figs. 9 and 10 it is seen that substantial thicknesses of aluminum with a yield strength of 60,000 psi will be required. Although 6-inch aluminum plates of this strength are commercially available, it is doubtful that aluminum plates can be obtained or developed in thicknesses greater than 6 inches and still maintain the required 60,000-psi yield strength. Thus, for the more typical hull diameters which require even thicker shells, aluminum may not be suitable for a military submarine. It may be important in the design of deep-diving research vehicles.

The shaping of plates to shell contour would require hot-forming methods; subsequent heat treatments would cause considerable distortion. But even these forming difficulties probably could be solved in time. The joining of the sections to each other offers difficult problems.

Metallurgically, aluminum is seriously affected by galvanic corrosion because of its high position in the electromotive series. The higher strength aluminum alloys are subject to stress-corrosion cracking, especially in the short, transverse direction of a plate or forging. Corrosion factors may be minimized by cathodic protection or by cladding, but any damage to such protecting media may cause serious deterioration.

Ballistic tests with high-explosive shells show that the higher the strength of aluminum alloys, the greater the tendency to crack or spall. If such cracking occurs under military attack or by corrosion damage, high hydrostatic pressures or additional dynamic loadings might lead to catastrophic failure.

With our present-day knowledge, weldable, corrosion-resistant aluminum alloys with yield strengths greater than 75,000 psi are not readily foreseeable. With this in mind, consideration of aluminum for military submarines may have to be shelved because of the large section sizes required, the lack of weldability, and questionable corrosion resistance and toughness under dynamic loads. Developments in design may change this picture.

(c) Iron-base alloys: It is easily seen from Fig. 10 that merely increasing the yield strength of steel (specific weight and modulus of elasticity remaining constant) increases collapse depth correspondingly.

It is theoretically possible to obtain a weldable iron-base alloy with 200,000-psi yield strength. Alloys with this strength have already been developed. Initial welding efforts with them have not been extensive, but they have not been entirely discouraging. It is conceivable that a welding procedure could be developed – and in the proper time scale. But would it be worth the effort?

Past experience with high-strength steels indicates that the higher the strength, the more difficult the problems of notch-sensitivity, stress-corrosion, and corrosion fatigue become. In addition to the difficulties with welding high-strength steels, the usually simple task of rolling becomes a major headache. For all these reasons, it appears that the 200,000-psi yield strength steel may not be a panacea. Iron-base alloys with a yield strength of 200,000 psi must continue to be studied, however, until titanium is definitely in the picture at 150,000 psi.

A steel of intermediate yield strength, say 150,000 psi, would be useful as an interim measure and the Bureau of Ships is pursuing this development to the limit.

Metallurgically, it is conceivable that a weldable, notch-tough steel can be developed with a yield strength of 150,000 psi. It seems likely that the same fabrication practices used today can be extended to a steel with a yield strength of 150,000 psi with some modifications. Heavier rolls will be required. Strict adherence to instructions and procedures will be required of the welder. Controls and enforcement of controls more stringent than those now in vogue will be mandatory. This is one of the prices of progress.

Many serious problems associated with 150,000-psi steel are anticipated. However, the route has been charted. Many details require resolution. The outlook for availability of this material within three or four years is bright. One signpost is clear: Welding electrodes and techniques must be developed concurrently with the material.

(d) Titanium: Perforce, titanium must be pitted against steel to determine the better contender for the long pull. But it must be remembered the year for use is not 1959 or even 1960, but more likely 1965 or later. Even with the rosiest of glasses it must be conceded that in that short a time steel will still have the edge in cost. But will it have the edge in performance?

Figure 10 categorically denies any superiority of steel. In fact, the limiting collapse depth for titanium is about 30 percent better than the best that steel can boast.

Characteristic of a young industry (and titanium development must be considered barely beyond infancy) are optimism and speed. Even so, a weldable 150,000-psi titanium alloy in thick plates is not yet a production reality. The 200,000-psi yield strength iron alloy is still in the laboratory phase. It seems highly probable, however, that titanium with a yield strength of 150,000 psi in the thicknesses needed may be available commerically sooner than will steel of 200,000 psi.

Although neither steel nor titanium of the strengths and thicknesses required has been formed under shipyard conditions, it appears that the same type of equipment and the same controls will be required. This factor must be investigated.

Little is known of the notch toughness of titanium alloys in heavy sections. What is known indicates that notch toughness is dependent on the purity of the base titanium sponge used in manufacturing the alloy. Although the method of fracture in titanium is different from that in steel, the meager information available for alloys of each of these materials of the strengths and thicknesses being considered here indicates that there is little to choose between them as to notch sensitivity. Comparative tests, using any of the many notch-toughness tests, will be conducted. For example, a series of explosion bulge tests conducted to determine the transition from ductile to brittle fracture would be desirable.

At present, welding of titanium must be carefully controlled because of its high absorptive tendencies at high temperatures. Similarly, the welding of high-strength steels must be carefully controlled because of the high probability of cracks if the moisture content of electrode coatings and the preheat temperature of base metal exceed narrow limits. If rigid enforcement of controls and improved technology are assumed, neither problem is insurmountable.

From all available information titanium alloys are immune to sea-water corrosion in marked contrast to the behavior of steel. This is a strong factor in the favor of titanium.

There is little information on tensile-creep properties of titanium at ambient sea temperatures and none at all on compressive creep. Here, again, is a void of ignorance which must be filled.

This comparison of titanium at 150,000 psi and steel at 200,000 has shown the superiority of steel as to cost and creep resistance, and a lack of data as to formability, notch toughness, and weldability. Titanium excels from the standpoint of limiting collapse depth and corrosion resistance. The Bureau is pursuing a program on both metals since, at this point, both have possibilities of ultimate success.

RESEARCH PROGRAM

Characteristics of Ideal Material

The ideal material is one which would have a very high modulus of elasticity and compressive yield strength, low density and transition temperature, corrosion resistance in marine atmospheres, be cheap and available in quantity in large plates and extrusions of heavy sections, isotropic, does not creep at high compressive loads, and could be cold- or hot-formed and welded by shipyard techniques without preheating or postheating and have 100-percent weld-joint efficiencies.

Materials for Consideration

Aluminum - Aluminum alloys are not escaping our attention. Alloy 7079 plate and forgings, while offering many problems in fabrication and unknowns as far as notch toughness under explosive loading, is being scrutinized for submarine service.

Titanium - Through the Department of Defense' titanium-alloy sheet-rolling program, a major effort of evaluation of titanium-alloy plate is underway. At least eight alloys, representing alpha, alpha-beta, and beta-alloy systems, from all major producers will be tested. Notch toughness of base metal and welded plates as thick as two inches will be determined. In addition, a welding program to devise methods of joining heavy plate is programmed.

The specifications for the titanium-alloy and weld-metal characteristics are essentially the same as given for the 150,000-psi yield strength steel, except that the parameters for creep resistance and endurance properties under plastic strain fatigue conditions are as follows: The alloy we want should have minimum creep at room temperatures, and lower, at stresses approaching the compressive yield strength. The alloy should possess plastic fatigue characteristics so as not to fail in 10,000 cycles from 150,000-psi compression to 75,000-psi tension.

Iron Alloys - Our efforts are directed to the needs of the current building program and to what the future may offer in major increases in strength, formability, and weldability.

The welding of heavy sections of HY80 steel requires very carefully controlled conditions of preheat and electrode application. We are studying the whole welding process in an effort to determine the effects of impurities in the base metal and, indeed, the whole welding environment on the integrity of the weld as made in the field. Fatigue studies are underway that will establish strengths of welded sections subject to cycling in simulated submarine environments. The extrusion processes for the production of frames are receiving attention.

We have announced sponsorship of research leading to the development of a 150,000-psi yield material in heavy sections, with good notch-toughness characteristics, that can be readily fabricated and joined under conventional shipyard conditions. It is our firm belief that alloy and welding development must proceed simultaneously.

CORROSION

One other aspect of submarine operation that must be kept in mind is the problem of corrosion.

Carbon and low-alloy steels corrode in sea water at the rate of 0.005 inch per year. Normal pitting rates are about twice that. Aluminum superstructures and masts, used to reduce topside weight, corrode rapidly when in contact with steel. Reinforced plastic materials for submarine fairwaters, platforms, and sonar domes have been investigated and certain trial installations made. These appear to be generally satisfactory. Corrosion of propellers, shafting, and fittings is generally no greater than for other classes of ships. At greater depth, shaft sleeve corrosion has been noted to be more serious. Cavitation erosion of propellers is of concern in operation at moderate depths. Figures 12 and 13 show a World War II submarine in drydock. One can see the effects of sea-water immersion after a normal waterborne period.

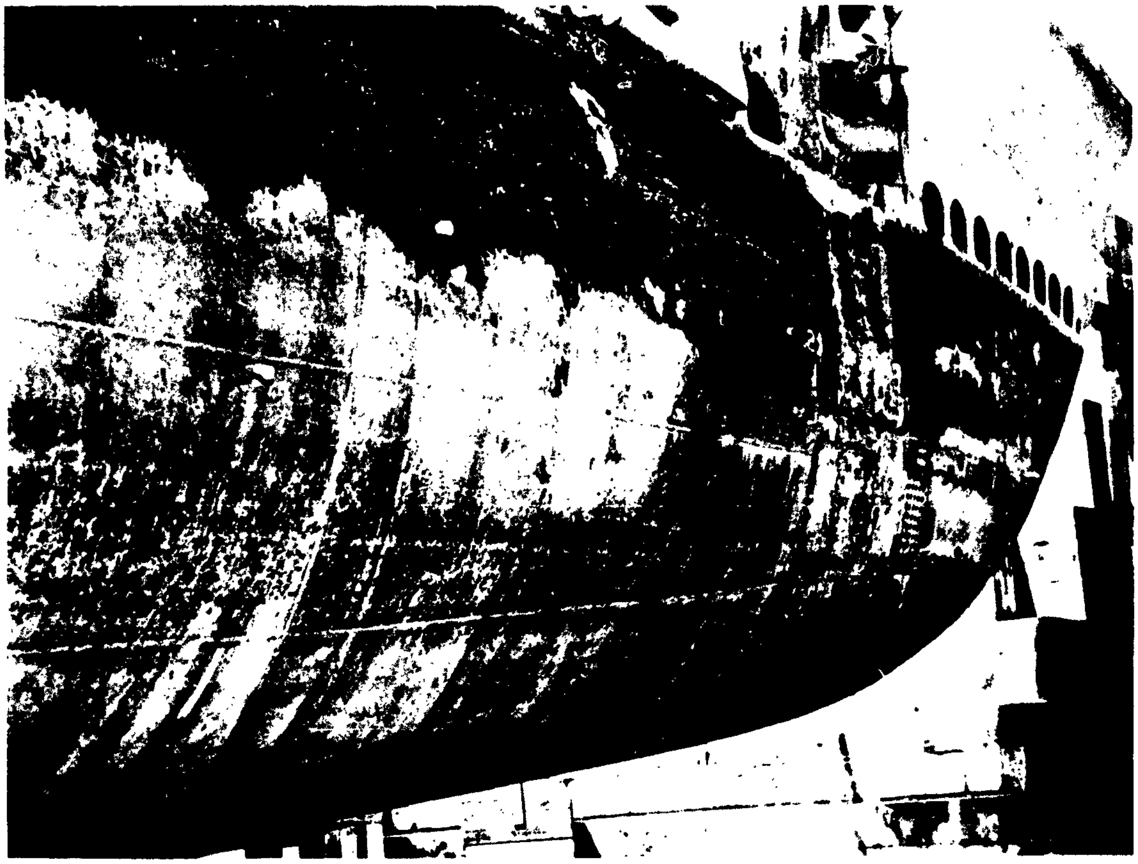

Fig. 12 - Effects of sea-water immersion on a World War II submarine

The deep-diving submarine corrosion is even a more important material problem. This applies, of course, to external hull surfaces as well as to machinery components. For example, the detail specifications for new submarines call for additional thicknesses of hull plate beyond that required by design. This extra metal is required just to take care of possible thinning due to future corrosion. With steel weighing 0.28 lb/cu in. it is readily apparent that a corrosion-resisting alloy for hulls would be welcomed. Also, since the corrosion fatigue limit of structural steel is about 8000 psi regardless of strength, structures subjected to repeated stress, while unprotected in sea water, are vulnerable.

Due to submergence of the submarine, condenser tubes now are required to take full submergence pressure and thinning due to corrosion now becomes a possible source of trouble. Accordingly, condenser tubes are specified to be heavier than on surface vessels.

Fig. 13 - Effects of sea-water immersion on a World War II submarine

The corrosion of shaft journals in the way of syntron seals is a particularly annoying problem. The various "fixes," such as rubber, epoxy, etc., which have been tried have not been successful. A cobalt alloy may be the answer.

The most insidious form of corrosion found in marine service is stress-corrosion cracking. In the fleet this has been a problem with certain brass and steel components. Over the years, techniques and alloys have been developed to minimize the difficulty. With the event of the nuclear power plant, the problems became more acute. The use of austentic corrosion-resisting steel as a standard construction material for nuclear-powered systems is fraught with dangers of stress-corrosion cracking both from internal (secondary water systems) and external corrosion. Salting of the system from a leaky condenser, contamination of a lagging with sea water, or caustic concentration in crevices can result in stress-corrosion cracks in the piping, joints, flexible connections, etc. Extreme diligence in water chemistry control is necessary to minimize the problem. Current investigations indicate that "Inconel" will be a satisfactory material for pumps, piping, etc., for the nuclear-powered reactor plant and is being specified.

The Navy goes to extreme lengths to guarantee the integrity of the pressure hull. After five years of ship life, a very detailed structural survey of the hull is made at each overhaul. These investigations are very costly and time consuming. They show up those places where repairs must be made, however. Every effort must be made to improve materials and protective methods that will preclude the need for concern as to the condition of the pressure hull.

OTHER PROBLEMS

Time permits only brief mention of other metallurgical problems, the solution of which will contribute to our deep-diving capability. We feel that advances in the solid-state metallurgy are needed for the development of improved sonar materials for operations at deep depths. New power systems for propulsion and auxiliary use will depend in large part on studies of thermoelectric and thermionic power materials and containment systems for their application. Noise problems associated with high-power, high-speed propulsion systems will be resolved in part by metallurgical advances.

SUMMARY

We have shown the need for, and feasibility of, a military deep-diving submarine for operation at depths many times greater than those of existing submarines. For reasons of security, data regarding depths have been on a relative basis, and current and projected depths of operation have not been mentioned. Certain metallurgical problems associated with submarines and the need for solution of these problems have been discussed.

Insofar as pressure hull structure is concerned, it is feasible to design a cigar-shaped pressure vessel with sufficient buoyancy and volume to carry crew, weapons, propulsion equipment, and supplies which will be operated as a submarine at "deep" depths.

The selection of a metal for hull construction has been discussed with emphasis on the criteria for usefulness. Advantages and disadvantages of aluminum, steel, titanium, and beryllium have been explored in the light of these criteria. New alloys, or at the least a new outlook on fabrication, test, inspection, and control of known alloys, will be required with current emphasis being placed on iron-base and titanium-base alloys.

Finally, we must do all in our power to protect our investment by a selection of material and protective measures for the control of deterioration, both within and without the pressure hull.

Solutions to the technical problems must come from the Navy's strong programs of research and development in basic materials and science helped by all the effort and thinking that industry, universities, and laboratories can offer. The Navy's position is that such a program is vital to its mission of control of the seas.

ACKNOWLEDGMENT

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MATERIALS REQUIREMENTS OF HYPERSONIC FLIGHT VEHICLES

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ABSTRACT

The large number of possible flight vehicles may be reduced to certain basic types, according to their function. The function may be described in terms of altitude-velocity flight profiles and flight times for the case of aerodynamic heating and in terms of range or payload capabilities for the case of propulsion.

Aerodynamic heating results from the high-velocity flow of air over the surface of the body. Depending on the altitude, velocity, form, and distance from the leading positions, a boundary layer of gas having a specific temperature will be developed. The hot layer delivers a heat flux to the structure that results in the attainment of a specific temperature, determined both by the time of exposure and the infrared emissivity characteristics of the surface.

Thermostructural solutions to the aerodynamic heating problem may be based on either absorptive or radiative thermal protection systems. Absorptive systems are based on accepting and storing the heat-flux input; such solutions apply to pulse, or short-time, heating conditions. Radiative systems are based on radiation cooling; such solutions apply to the case of long time exposure to the heat flux. The index of merit of absorptive systems is the heat storage capacity per pound of thermal protection weight. For radiative systems the essential requirement is for the development of materials that have the highest possible structural efficiency for the temperatures involved. High infrared emissivity is desired for purposes of minimizing the temperature level that is attained.

The materials problems of rocket propulsion relate both to the high temperatures of the combustion process and the rigid requirements for minimum inert-parts weight. The basic aspects of the propulsion problem may be described in terms of the specific impulse (I_s) of the propellant and the mass ratio (W_i/W_f) of the rocket. In order to develop high specific impulses, it is necessary to maximize the combustion temperature and to minimize the molecular weight of the exhaust gases. The first requirement results in the use of propellants that have flame temperatures of about 5000^0 to 6000^0F. The requirement for low molecular weight leads to the use of nuclear rockets with

hydrogen as the propellant. For liquid-fueled rockets, the nozzles are cooled by counterflow of the propellant through the nozzle wall prior to entering the combustion chamber. For solid-propellant rockets it is necessary to use absorptive system cooling, involving thick walls of refractory metals, graphite, or ceramics.

The requirement for minimum inert-parts weight for the construction of solid-propellant rocket motor casings places a premium on the use of materials having very high strength-to-density ratios. In this case, the primary problem involves the selection of materials and fabrication procedures that provide for reliable performance of highly stressed, thin-wall pressure vessels. The presence of flaws in the chamber or closures may result in tear ruptures or shattering, depending on the properties of the material.

The control of satellite body temperatures is critical because of the relatively small deviations that may be tolerated by the electronic components, photographic equipment, etc. A discussion is presented of the factors involved in radiation heat exchange of satellite bodies, particularly as related to the optical properties of the surface.

* * * * *

INTRODUCTION

It is generally recognized that the future attack and defense capabilities of the Navy are greatly dependent on the utmost exploitation of missiles, rockets, supersonic aircraft, and satellite systems. The operational effectiveness of these various devices depends on a number of factors that include the specific design, the electronic components, fuels, and materials. The importance of materials to the performance, and in many cases the feasibility, of new systems has been highlighted in recent years by the realization that many design requirements could not be satisfied by available materials. This situation is not surprising because many of the present systems are based on using available materials to the limits of their capabilities; therefore, even marginal improvements in performance hinge on the results of the present day efforts of materials laboratories. Concepts and designs that call for major jumps in performance, the "quantum jump" philosophy, are repeatedly stymied by the hard fact that suitable materials may not be available for a long time. In such cases, the operational date of the system is determined entirely by the rate of effort on the materials phase of the project.

The aspects of extreme temperatures associated with the re-entry of nose cones have been publicized widely as a major problem in the area of materials. The fact that solutions have been obtained within a reasonable time for such extreme environmental conditions is often misinterpreted to signify that other, less extreme, conditions will be resolved more readily. Actually, the nose cone problem yielded to concentrated attack on a major scale and the solutions that were obtained are specific to the short-time, high heat-flux environment of nose cones. This experience does not help in any way with the problem of extended exposure to moderate heat-flux environments that are characteristic of various missiles and hypersonic aircraft.

The materials problems of this new era are many and diverse. The amount of effort and the probability of success cannot always be gauged in relation to the extremes of the environment and on assumptions as to the relative difficulties of coping with various environmental conditions. Examples of less glamorous, but nevertheless critical, materials problems include: corrosion resulting from reactive substances such as acids used for fuels; resistance to brittle fracture at low temperatures associated with the use of liquified gases; resistance of organic materials to ionizing radiation, ultraviolet radiation, and vacuum environments of space; and fabricability of new metals such as beryllium.

The complexity of the materials problems evolves not so much from the requirement of high performance in terms of a specific property but from requirements involving exacting combinations of properties. The desired combinations often include such oppositles as high strength coupled with low density and high ductility. In fact, it sometimes appears that the designer simply spells out complex materials requirements in terms of what it takes to make a system operable, and then urges the materials laboratories to fill the bill. The difficulty today is that the magnitude of the effort is often grossly underestimated, leading to unrealistic planning of the lead time for the development.

Within the limitations of this brief article, it is not possible to describe in detail the materials requirements for all of the environmental conditions of flight systems. The presentation will be aimed at developing a sufficiently comprehensive spectrum of the materials requirements for the purpose of indicating the general direction and magnitude of the future research effort. In effect, the materials problems will be described in terms of the principles of flight, propulsion, and energy transfer that establish the requirements for the materials.

A broad separation of flight vehicles may be made in terms of aeronautical and astronautical systems. In conventional terms, the separation relates simply to the conditions of flight as being respectively within and outside the atmosphere of the earth. Such a separation is much too broad to provide useful definitions of the nature of flight for purposes of discussing materials requirements. As a first step, it is necessary to discuss the flight conditions of the various types of vehicles. However, before even this can be done, we must consider the nature and limits of the atmosphere of the earth.

The most striking aspect of the atmosphere is the small amount of air which is coexistent with the earth. If this total amount of the air were reduced to normal pressure and temperature, it could be contained in a band approximately 5 miles thick. Actually, the density of this blanket of air falls off exponentially with increasing altitude such that 99 percent lies within 100,000 feet (20 miles). The aeronautical limits of atmospheric space, based on air breathing propulsion systems, including ramjets, reach to about 150,000 feet (30 miles). A functional limit of flight by aerodynamic lift may be established at about 300,000 feet (60 miles). For altitudes in the range of 150,000 to 300,000 feet the propulsive power must be derived from rocket motors or from rocket boost, followed by glide. This zoning provides for a separation of aeronautical flight generally considered as earth bound operations, and space flight marked by satellite orbit flight or short-time ballistic and thrust flight in space.

Satellite orbit flight may be defined as operating in the gravisphere regime of the earth, i.e., in regions where the effects of the earth may be expressed in terms of its gravitational attraction. Figure 1 illustrates this separation in terms of the distances from the earth. Compared with the earth's radius of 4000 miles, the 60-mile band of atmosphere involved in aeronautical flight and deceleration of re-entry vehicles is extremely shallow. Above 60 miles the atmosphere may be best described in terms of distances of separation between individual molecules of gas, first in terms of feet then progressively to separation distances of miles, at altitudes of 300 miles or more. In other words, the technical limit of the atmosphere (TLA) roughly marks a region of change from atmospheres involving a gas continuum to atmospheres involving free molecules of gas. Because of the residual gas present at altitudes in the order of 100 to 200 miles, satellite orbits of this altitude range are of relatively short duration. Permanent orbits require minimum altitudes in the order of 300 to 400 miles. The TLA also marks the approximate limit of aerodynamic heating (thermospheric flight) of high-speed bodies by the flow of gas over the skin. Above this limit, heating of the skin may occur only by radiation from the sun.

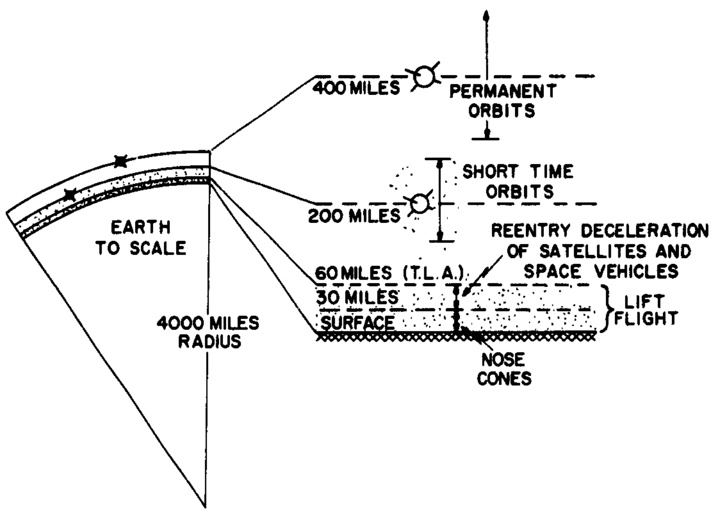

Fig. 1 - Altitude separation of various flight regimes

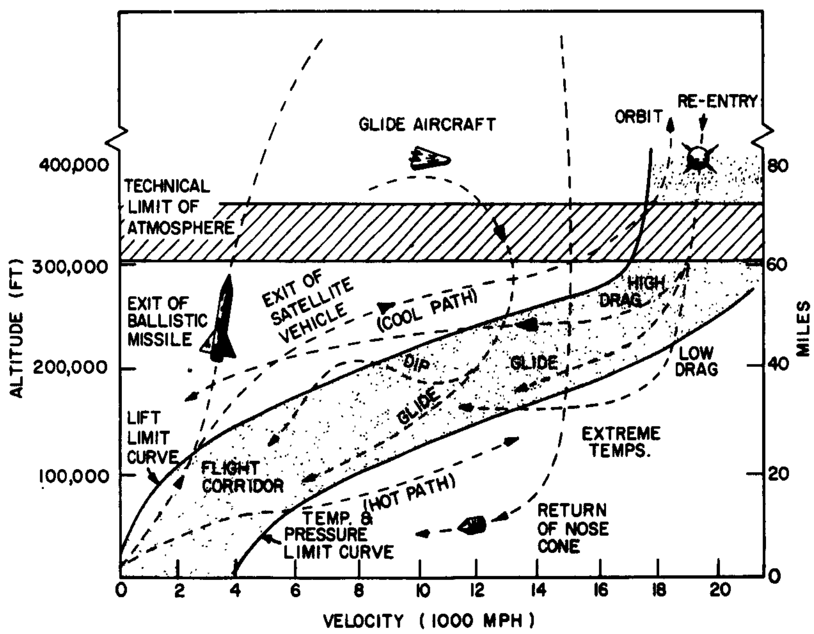

Fig. 2 - Characteristic flight paths of various vehicles

The apparently infinite varieties of thermal flight vehicles in the news may be reduced to logical groupings codified by altitude, speed, lift, and propulsion features. These features basically determine the form, construction, and the thermal environment. Figure 2 illustrates the various possible vehicle flight paths in terms of altitude-velocity regimes available for lift, thrust, and re-entry flight. These regimes are strictly determined by nature of the earth's atmosphere and are subject to calculation, based on physical laws.

The usual starting point in a description of flight regimes is the concept of the flight corridor. The corridor describes a zone of continuous level flight with lift, commonly referred to as aerodynamic cruise. Aerodynamic cruise vehicles use wings to obtain lift; the amount of lift is defined in terms of pounds per square foot of wing surface and is a function of forward velocity of the vehicle and angle of attack of the wing with respect to the air-stream. Because of the decreasing density of the air with increasing altitude, obtaining the necessary minimum value of lift requires flight at higher velocity with increasing altitude. For any given altitude, the lowest velocity of flight is determined by this aerodynamic limit and the highest velocity is established by materials limits related to the development of excessively high temperatures or pressures. In the subject figure, the materials limit is arbitrarily taken as the velocity that results in aerodynamic heating of lifting surfaces to 2000°F. The velocity that is required to establish this temperature increases with increasing altitude. For altitudes of less than 70,000 feet, excessive aerodynamic pressures are developed in the region beyond the temperature limit curve. The open end of the flight corridor represents the attainment of velocities required to establish orbital flight. At such velocities the body develops sufficient centrifugal force to offset the attraction of gravity, and lift is no longer required for flight.

Flight outside the corridor is primarily restricted to re-entry vehicles and boost vehicles that depend on rocket thrust for support. Boost vehicles may actually take any flight path within the diagram. Hot and cool thrust flight paths—high and low skin temperatures—are indicated for purposes of illustrating two characteristic flight programs. The hot path is not practical for satellite launching vehicles or for ballistic missile boosters, because of the very high fuel consumption rate that would be required for high-speed propulsion through the dense atmosphere and because of the high skin temperatures generated by such flight. The fuel requirement would be extreme if the flight followed a path through the region beyond that described for the hot path; in fact, nuclear power systems would be required to produce the necessary thrust because of the high pressures that would be generated by the airflow. Boost flight for a short time along the hot path is a requirement for antimissiles that must reach high velocities at relatively low altitudes in order to intercept nose cone warheads.

The cool path represents a gradual increase in velocity with increasing altitude. It is the general path taken by satellite launching vehicles that must attain orbital velocities outside of the atmosphere. Fuel is conserved by such maneuvers because aerodynamic drag is kept to a minimum and heating is quite moderate. The curve that rises almost vertically and then bends downward represents the characteristic exit flight path for long-range ballistic missiles, the continuation of which is noted by the re-entry flight path of the nose cone. The boost phase of the flight terminates along the upper curved portion—outside of graph—and the flight then continues downward on a purely ballistic fall trajectory. Atmospheric drag causes a sudden deceleration of nose cones at some critical altitude, as indicated by the sharp drop to lower velocities at altitudes in the order of 50,000 feet. Extreme heating is developed during the essentially shock-like deceleration phase.

Satellite vehicle exit paths also roughly approximate the path taken by the booster for a manned glide vehicle that attains orbital velocities. Such a path is dictated by requirements for immediate transition to glide flight in case of power plant malfunction at suborbital velocities. If the glide vehicle is a nonorbiting, short-range glide type, such as the X-15, the exit flight path may be steeper, i.e., it may approach the ballistic missile exit path. The peak altitude portion of such a path is shown by the curve that bends over outside the TLA and then indicates a ballistic fall path towards the flight corridor. As the glide vehicle falls to altitudes within the flight corridor, the air density becomes sufficiently high to provide lift to the wing surfaces and glide flight is developed. The glide path is indicated by the curve that follows the lower limits of the flight corridor. If the vehicle carries a small rocket propulsion motor, it may first follow a glide path, then a momentary burst of power increases its altitude above that of the flight corridor. Such dips in and out of the flight corridor provide for the cooling off of vehicles that have limited heating capabilities, such as the X-15. In essence, if the temperatures begin to approach the capabilities of the structure, the vehicle seeks a higher altitude that results in lower temperatures for the same velocity.

Satellite re-entry of the atmosphere is indicated by the three flight paths for the return of orbiting vehicles. In order to appreciate the significance of these curves, it is essential to discuss the re-entry problem in general terms. Consider a satellite orbiting the earth at altitudes in the order of 300 miles. Such a body will have a velocity in the order of 18,000 mph. If a small retroactive rocket is fired so as to reduce this velocity slightly, the vehicle will then have less than orbital velocity and will dip into the atmosphere at a grazing angle. The high-speed airflow against the body results at first in a gradual deceleration, which is followed by a shock-like deceleration (for nonlifting, i.e., drag bodies) as atmosphere of higher density is reached at lower altitudes. The altitude of shock-like deceleration depends on the aerodynamic drag-to-weight ratio of the body. As illustrated in Fig. 2, a high-density body–low-drag-to-weight ratio–will penetrate to low altitudes before it suddenly decelerates to low velocities. A high-drag-to-weight ratio body will decelerate at higher altitudes and with a decrease of the shock-like aspects.

Manned re-entry vehicles, based on drag flight principles, are represented by devices such as the Mercury capsule. This is essentially a blunt body, designed to give a relatively moderate deceleration within the 8-g limit of man's ability to absorb such forces. The feature is simplicity of construction and quick return to earth. It has little or no maneuverability and must be injected into the atmosphere with exact angle and timing, if it is to fall to a predetermined location. The re-entry flight path of such a vehicle will approximate that of a body of intermediate drag-to-weight characteristics.

The other manned type is a glide re-entry vehicle that is essentially a hypersonic aircraft. On injection into the atmosphere the vehicle may be programmed to present a high angle of attack to the airstream so as to develop a combination of high-drag and high-lift forces. Such a vehicle slows down gradually with a maximum of 2-g deceleration and follows a glide path within the flight corridor. After slow-down to subsonic velocities, it glides to a selected landing site.

AERODYNAMIC HEATING

The problems that were faced in conquering the sound barrier were principally aerodynamic in nature. By developing proper designs or form of the aircraft and sweep-back of the wings, it was possible to alleviate a sharp rise in drag, or aerodynamic resistance, as the flight velocity approached the velocity of sound. The heat barrier cannot be circumvented in a similar manner. The heat barrier does not involve a definite limit at some flight velocity, but becomes increasingly severe with increased velocity. From a practical viewpoint the barrier may be considered to become a structural problem beyond about Mach 2.5.

A body propelled through the air displaces air particles, producing compression at the leading positions where the air is pushed out of the way. A thin boundary layer is also developed over the surfaces. The physical process of aerodynamic heating is illustrated schematically in Fig. 3. Ahead of the moving body, molecules or air exist in random motion, with a density of state determined by the altitude, a random velocity characteristic of the ambient temperature, and a pressure determined by the impulse of random collisions. The approaching body captures a volume of the air, compressing a portion statically against the leading position. The approach of a high-speed body with its envelope of compressed gas results in a shock-like impact on the molecules in the path of flight. The shock envelope that is developed represents the limit of the pressure disturbance surrounding the body. The compression process entails a conversion of the energy of motion into heat. The region of compressed gas that piles up at the leading point of the body is termed the stagnation point. Regions back from the stagnation point are subjected to high-speed flow of gas in a streamline layer, called the

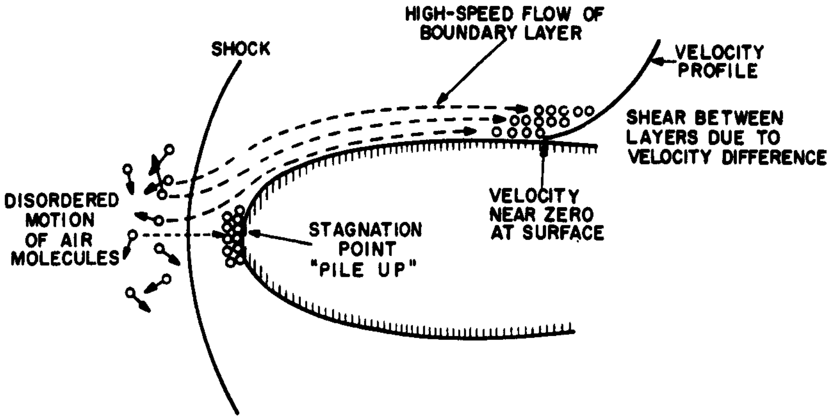

Fig. 3 - Nature of aerodynamic heating processes at stagnation points and at positions involving boundary layer flow

boundary layer. The velocity of the boundary layer decreases rapidly near the skin, approaching near-zero velocity at the skin surface. The velocity profile through the boundary layer provides for the development of shearing forces between the various levels of the boundary layer and a consequent rise in temperature of the gas. In a very crude way we may describe the heating process as due to adiabatic compression at stagnation points and due to viscosity over the regions back from the stagnation points. The important fact is that the higher the velocity and the higher the density of the gas (lower altitudes) the higher will be the temperatures of the stagnation point regions and the boundary layers. The temperatures attained by the gas envelope at stagnation point regions are much higher than for regions back from the stagnation point.

The hot gas layers transfer heat to the surface of the body by convection. The value of the heat flux is proportional to the heat-transfer coefficient and the difference between the boundary layer and skin temperatures. Figure 4 illustrates the process of aerodynamic heating. The solid line illustrates a decreasing value of the heat-flux input to the skin as the skin temperature rises. The dashed lines, relating different values of surface emissivity, illustrate an increasing value of radiative heat flux as the skin temperature rises. The input heat flux and the radiative output heat flux will tend to come to a balance or equilibrium at some specific temperature level of the skin. Since the balance point represents a steady-state condition—heat-flux input = heat flux radiated to space—the temperature level of the skin will likewise remain fixed as long as the flight conditions remain unchanged. The temperature that is established depends on the emissivity of the surface, e.g., increasing the emissivity results in decreasing the equilibrium temperature because the surface becomes a more efficient radiator. It should be noted that the highest emissivity that a surface can have is that of a "blackbody," for which $\varepsilon = 1.0$; such a surface establishes the lowest possible radiative equilibrium skin temperature for any given condition of flight.

CONSTRUCTION FOR STEADY-STATE AERODYNAMIC HEATING

Radiative equilibrium temperatures are developed only if the flight conditions involve steady-state aerodynamic cruise or long-range glide. This implies lift flight vehicles, featuring airfoils or wings for support, as contrasted with rocket thrust flight vehicles, and drag flight vehicles, such as nose cones. The latter types generally do not maintain a fixed velocity

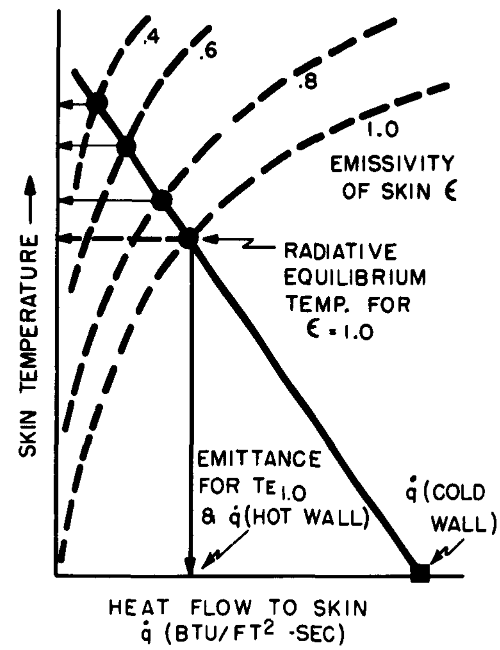

Fig. 4 - Relationships of radiative equilibrium temperatures to aerodynamic heat input and surface emissivity factors

and altitude; therefore they do not attain thermal equilibrium. Because of the transient nature of the stagnation point and boundary layer heat flux, thrust flight and drag flight vehicles may be designed on principles of absorbing the heat input rather than radiating the heat back to space. For example, nose cones may be designed on either heat sink or ablation heat absorption principles.

The general levels of radiative equilibrium temperatures that may be expected for flight at various combinations of velocities and altitudes are illustrated in Fig. 5 for a sharp nose and for a flat surface, such as the pressure side of a wing. In both cases, high values of emissivity of the skin surface were assumed. The temperatures of the sharp nose are noted to be much higher than those of the underside surface of the wing. In comparison, the temperatures for the leading edge of the wing would be higher than those of the underside surfaces, but not as high as those of the nose. It is important to recognize that the local contours determine the temperature of the gas envelope at the various positions of the body. For example, increasing the sharpness of the leading points results in developing higher temperatures for the same velocity-altitude conditions of the body. The point to be emphasized is that the local airflow and pressure conditions determine the temperature rise; therefore, it is necessary to discuss aerodynamic heating in terms of a given shape. The values cited are typical of the general temperature conditions that are involved in the design of highly-streamlined bodies representative of hypersonic aircraft and missiles.

The location of the flight corridor has been noted in Fig. 5 by the dotted area superimposed on the temperature plots. We may now consider the implications with respect to the materials of construction. The parameter yield strength divided by density provides the basis for comparison of temperature capabilities, because the determining factor is the weight efficiency of the material. If the airframe stresses are high, the high-strength aluminum alloys are useful to approximately 200°F. The high-weight efficiencies of the aluminum alloys may be retained by the use of high-strength steels or titanium to approximately 800°F. Between 800° and 1000°F, steels may be used with somewhat lower weight efficiency. Between 1000°

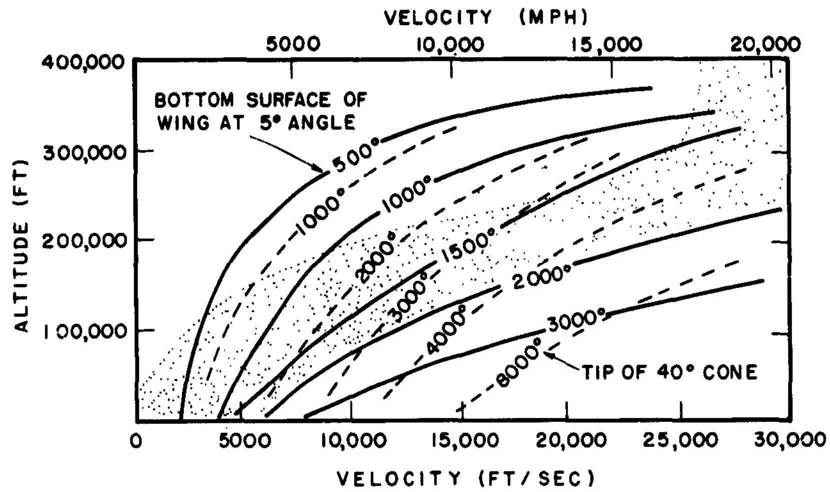

Fig. 5 - General level of radiative equilibrium temperatures for positions involving sharp nose and flat surface contours

and 1500°F it is necessary to change to high-temperature alloys, that have relatively high-density and low-maximum strength; accordingly, the weight efficiency falls to low values. Above 1500°F it is necessary to use molybdenum or columbium alloys that have low-weight efficiencies. For example, construction of molybdenum airframes entails a weight of approximately 3.5 times that of room-temperature airframes of the same load-bearing capacity. This comparison is based on tensile stresses. If the particular construction is critical in compression and the stresses are low, it is possible to use the various metals to somewhat higher temperatures before a change to the metal of the next temperature range is required. However, if the stresses are high, the compression analysis leads to essentially the same conclusion as for the case of tensile stresses.

We may now zone the flight corridor in terms of the primary metals of construction for flight at various altitudes and velocities (Fig. 6). It is apparent that these various metals provide for the construction required for any zone of the flight corridor. However, for the high-velocity regions of the corridor it is necessary to use molybdenum or columbium. The high-weight penalty that is associated with such construction suggests designs other than the conventional "hot structure," i.e., with load-bearing members subjected to the high temperatures. The alternate method entails insulating the skin from the supporting spar members and cooling to offset the leakage of heat through the insulation. Such construction is termed insulated radiative heat shield design. Figure 7 (top) illustrates the general features of hot structure and radiative heat shield construction. It should be noted that the skin of the radiative heat shield carries no load other than the wind load and simply rests on insulation supported by the internal structure. Its primary function is one of directing the airflow and of dissipating the boundary layer heat input by outward emission to space.

The leading edges and nose regions of hypersonic aircraft and missiles provide more formidable structural problems. Temperatures associated with velocity-altitude conditions requiring the use of molybdenum for "positions back," may be in excess of the melting points of molybdenum for leading positions. Such positions may require the use of graphite and carbide surfaces or metallic surfaces cooled by closed system circulation of liquid metals. In the latter case the liquid metal is pumped to cooler regions that act as radiators.

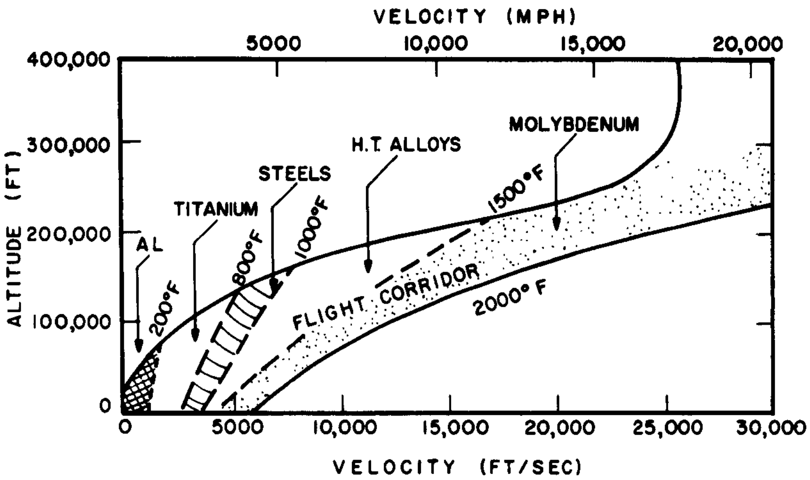

Fig. 6 - Construction material required for lifting or control surfaces of cruise and glide flight vehicles; the analysis relates to highly stressed components

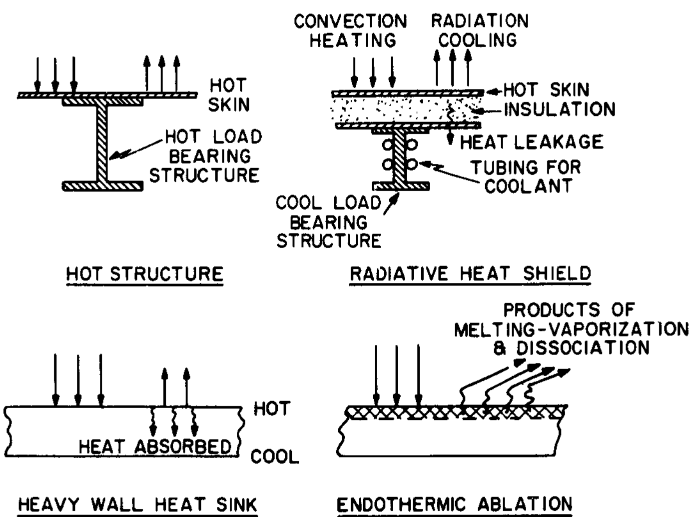

Fig. 7 - Structural features of radiative (top) and absorptive (bottom) thermal protection systems

CONSTRUCTION FOR TRANSIENT AERODYNAMIC HEATING

The flight path of long-range ballistic missiles and lifting vehicles for satellites generally consists of a boost phase through the regions of the flight diagram above the flight corridor. Propulsion requirements related to efficient utilization of the fuel, dictate a gradual increase in velocity with increasing altitudes, thus resulting in a relatively cool path for the rocket body. Aluminum and high-strength steels generally have been used for construction of the exit vehicle. The emphasis has been on attaining the lightest possible structure because the burn-out velocities developed by the vehicle are an exponential function of the ratio of the propellent weight to the structural weight.

Re-entry of ballistic missiles and satellites poses the most extreme thermal problems. The magnitude of the problem may be assessed by the fact that a body approaching the earth's atmosphere from high altitudes possesses a large amount of kinetic energy due to its velocity. The kinetic energy of a body returning to earth with escape velocity of 37,000 feet per second (25,000 mph) is in the order of 27,000 Btu per pound. For a ballistic missile nose cone of 23,000 feet per second (15,500 mph) re-entry velocity, the kinetic energy is in the order of 11,000 Btu per pound and for a 25,000 foot per second (17,000 mph) satellite, 13,000 Btu per pound. Considering part of the total weight as a payload, the total energy is sufficient to vaporize even a thick skin composed entirely of carbon, a substance that has the highest heat of vaporization. Obviously, this event would occur only if all of the energy were transferred to the vehicle as heat. Fortunately, only part of the heat resulting from conversion of the kinetic energy must be absorbed by the vehicle. A large part of the heat may be dissipated to the air in the shock envelope that surrounds the vehicle, and the remainder may either be absorbed or radiated from hot surfaces, depending on the specific re-entry maneuver.

The actual severity of heating for re-entry is directly related to the rate of deceleration of the body as it penetrates the atmosphere. Short time decelerations signify high rates of conversion of kinetic energy to heat, i.e., intense heat "pulses" representing high heat fluxes applied for short times. Long time deceleration provides for a gradual conversion of kinetic energy to heat with a spread-out heat flux, that may be handled in large part by radiative cooling. The time periods of exposure to high heat fluxes may vary from less than 1 minute for high weight, low drag, steep angle entry of long-range ballistic missiles to 10 minutes for low-density, high-drag spherical satellites approaching the atmosphere at a shallow angle.

The forces that act on a nonlifting-drag-body penetrating the earth's atmosphere, which increases exponentially in density with decreasing altitude, are a function of the weight-drag parameter $W \sin \theta / C_D A$ where W is the weight, θ the approach angle, C_D the drag coefficient, and A the frontal area. High weight and steep angle imply high inertial forces, while high-drag coefficients and large frontal area imply high-drag forces. The interaction of these opposing forces during re-entry results in developing a point of maximum deceleration and maximum heating during the period of penetration of the atmosphere. The severity of deceleration and heating depends on the approach velocity and on the altitude at which the maximum deceleration is developed. A high-drag, lightweight body will decelerate at high altitudes under "soft" conditions of aerodynamic resistance. Conversely, a low-drag, high-weight body will decelerate at low altitudes in dense air, with hard conditions of aerodynamic resistance. In the former case, the deceleration may be likened to the gradual penetration of an object into loose sand, while in the latter, the deceleration may be likened to the penetration into stiff clay. The maximum deceleration load is developed at a point where the velocity is decreased to approximately 0.6 of the original value. The maximum heating rate is developed at the point of 0.8 of the original velocity. This latter event occurs during the period of rapid increase in deceleration but before the peak is reached.

Inasmuch as the temperatures that may result from the high heat-flux conditions of drag re-entry are above the limits of available materials, it is necessary to absorb the heat that is transferred to the vehicle. The simplest possible solution to this problem involves the use of thick skin, heat-sink systems, Fig. 7 (bottom). Such systems are designed to diffuse the heat away from the surface sufficiently fast to prevent the attainment of melting temperatures during a short period of transient heating. The important property of materials for this purpose is a moderately high-melting point, combined with high-thermal diffusivity. The most efficient materials for heat-sink applications include graphite, beryllium oxide, beryllium, molybdenum, and copper. For the least severe conditions requiring the use of a heat-sink design, beryllium provides a low-weight solution. However, this material is noted for its toxicity and lack of ductility. For more severe conditions, graphite and beryllium oxide provide low-weight solutions. The problems of using such highly brittle materials presently restrict their applications. Molybdenum approaches the performance of graphite, but at a severe weight disadvantage. The manufacture of this material into a suitable structure would present difficulties, however, its ductility exceeds that of beryllium by a large degree. Copper provides for intermediate heat-absorbing capabilities but at the cost of a large weight penalty. This relatively cheap, highly ductile metal provides the only apparent solution which does not involve severe manufacturing, storage, and use problems.

Another method of heat absorption that could be considered, involves ablation–melting or vaporization–of materials with high heats of fusion or sublimation, Fig. 7 (bottom). Ceramics and organic materials are much superior to metals in the general process of ablation. Here, the design problem involves the development of combinations having optimum-performance characteristics for specific levels of heat fluxes. Carbon is unique in that it may be used both as a heat sink and as an ablation–sublimation–material. Transpiration cooling involving porous nose cones, that are cooled by the passage of gases or liquids through the pores, may be considered. Such methods generally involve pumping and control systems of undersirable complexity for re-entry bodies.

RELATIVE CAPABILITIES OF THERMAL PROTECTION SYSTEMS

A simplified summary of the aerodynamic input heat-flux capabilities of the various basic types of thermal protection systems is presented in Fig. 8. A broad separation is made between heating conditions involving short time exposures–pulse heating–and conditions involving steady-state heating. Detailed studies of the thermal exposure conditions of a wide range of thermospheric flight vehicles, suggests a practical separation of pulse and steady-state exposures in the range of 3 to 5 minutes. For exposure times of less than 3 minutes, the heating cycle ordinarily involves a bell-shaped, heat-flux pulse. For exposures in excess of 5 minutes a square-wave, heat-flux cycle generally is to be expected.

Pulse heating conditions may involve heat-flux inputs that would result in exceeding the melting point capabilities of any material of construction, if temperature rise is permitted. There is no question regarding the necessity of using absorptive systems of high heat capacity for such conditions. This environmental zone is denoted in the figure by the sketches representing transpiration, sublimation, and ablation thermal protection systems. The corresponding heat fluxes may range from 500 to 10,000 Btu per square foot per second.

Pulse heating conditions, involving heat fluxes in the range of 50 to approximately 500 Btu per square foot per second, require the application of heavy-wall heat-sink systems. For heat fluxes of less than 50 Btu per square foot per second, the shell of the vehicle–missile body, for example–may provide the required thermal capacity, if the exposure time is less than 1 minute. For exposures of several minutes, it is necessary to augment the thermal capacity of the shell by the use of one of the following devices:

(a) water cooling–tubing, spray, soaked mat, etc.,
(b) transient external insulation (transulation), or
(c) ablation of inorganic films, such as teflon.

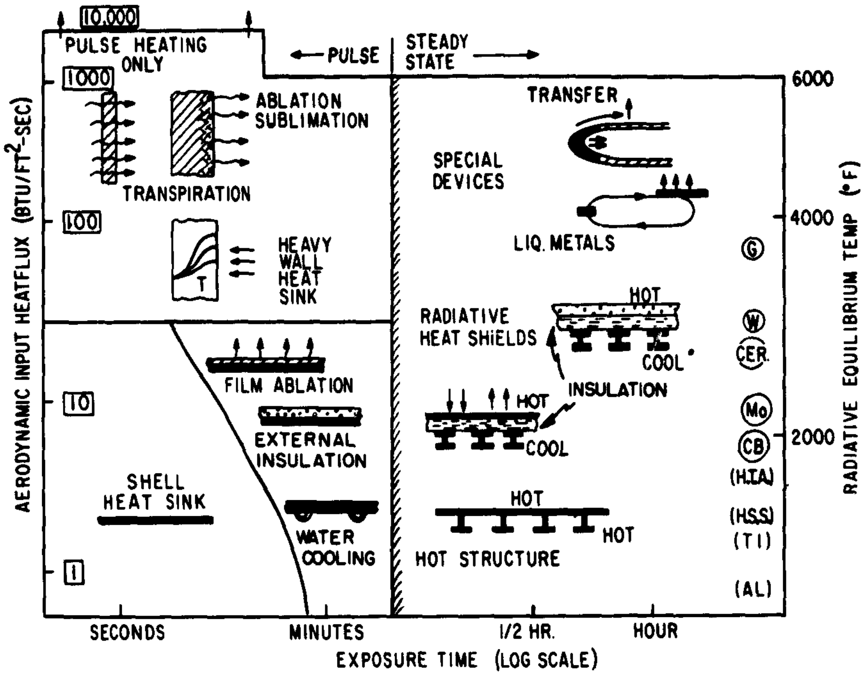

Fig. 8 - Summary of heat-flux and exposure-time capabilities of various types of thermal protection systems

These comparisons consider both weight and heat-flux capabilities. In fact, the reason for eliminating the use of absorptive systems beyond an exposure time of approximately 5 minutes is the very great weight of the absorptive material that is required. For long-time exposures it is necessary to radiate a large amount of the convective heat input in order to provide reasonable design weights. This fact is immediately apparent on considering that the heat load for exposure times in the order of 1/2 hour may total 1/2 to 1 million Btu per square foot for leading edges of hypersonic glide vehicles. An absorbing material that has the relatively high-heat absorption efficiency of 2000 Btu per pound would require a weight of 250 to 500 pounds per square foot to accomplish this function. Radiative systems may be designed to radiate back as much as 95 percent of the aerodynamic heat input; thus, the absorptive capacity–for heat leakage–that is required may be reduced to reasonable values.

Various types of radiative systems are illustrated in the long-time exposure region of the diagram. For long exposures the proper reference for the environmental conditions is the radiative equilibrium temperature that is established by the aerodynamic heat-flux input. As the radiative equilibrium temperature is increased, it is necessary to use a range of materials of increasing temperature capability, as noted by the temperature levels referenced to aluminum, titanium, high-strength steels, high-temperature alloys, columbium, molybdenum, ceramics, tungsten, and graphite. It is noted also that the construction should normally change from hot structure designs to insulated radiative heat shields involving refractory metal surfaces, then finally to ceramic surfaces as radiative shields. At the highest levels of heat fluxes it may be necessary to remove a portion of the heat by conduction–transfer back–or by the use of pumped, liquid metal, closed cycle systems.

The thermal environment experienced by various types of thermospheric flight vehicles may now be related to the thermal protection system zones designated in Fig. 8, as follows.

1. Shell Heat-Sink Zone: Satellite launch rockets; IRBM and ICBM rockets, and short-range missiles.

2. Shell Augmentation Zone: Body of antimissile on exit; long-range missiles; drag re-entry of low-density satellites; and short-range, glide-flight vehicles.

3. Heavy Wall Heat-Sink Zone: Short- and intermediate-range nose cones; manned re-entry capsules; satellite dump; nose of antimissile on exit; and nose regions of future hypersonic missiles.

4. Transpiration, Ablation, Sublimation Zone: Nose cones of high ground-approach velocity (low drag).

5. Radiative Systems (500^0 to 1000^0F): Mach 3 aircraft and long-range supersonic ramjets.

6. Radiative Systems (1000^0 to 2000^0F): Mach 4 to 6 hydrogen and nuclear ramjets; and glide vehicles of short and intermediate range (X-15 types).

7. Radiative Systems (2000^0 to 5000^0F): Hypersonic glide re-entry vehicles; suborbital glide attack vehicles and missiles; lift re-entry capsules; and low-level, Mach 5 to 6, nuclear ramjets.

For the radiative systems, the high end of the temperature range relates to leading edges and nose stagnation points and the lower end of the range to positions back.

In discussions to follow, on thermal protection requirements of solid-propellant rocket nozzles, reference will be made of heat-sink solutions for first-generation systems. The heat-flux conditions of the nozzle throats are in the order of 100 to 500 Btu per square foot per second and the exposures may range from 0.7 to 1.2 minutes. The analyses presented in Fig. 8 indicate that heat-sink systems may logically be used for such conditions.

TEMPERATURE CONTROL OF SATELLITES

Because of the essential lack of atmosphere at orbiting altitudes, the heat-transfer problems of satellite bodies are considerably different from those described for vehicles operating within the atmosphere. Free molecules that exist at altitudes of 100 miles or higher, do not develop convective heating. Thus, the only significant heat-transfer process involves radiation heating of the skin caused by solar flux or cooling due to radiation to space. The thermal problem in this case does not primarily involve the structure of the satellite, but rather the delicate electronic equipment comprising the payload. For this reason the concern is with relatively small temperature changes.

The factors involved in the temperature control of satellites are illustrated in Fig. 9. The spectral distribution of the solar flux is concentrated at short wavelengths in the range of 0.3 to 2μ. This distribution is determined by the high temperature of this source. The integrated value of the flux is in the order 0.12 Btu per square foot per second near the earth. The emission spectral distribution of a surface operating at near ambient temperatures, say 100^0F, is spread out over a range of long-infrared-wavelengths in the range of 8 to 20μ. The intensity of the emission of such a low-temperature body is relatively low. In Fig. 9 the scale for the low-temperature spectrum is represented at 10 X scale compared with that of the sun energy spectrum. Obviously, low-temperature bodies are poor emitters; thus, if a large temperature rise is to be prevented, it is necessary to adjust the optical properties of the satellite surface so as to provide for low absorptivity at short wavelengths and high emissivity at long wavelengths. The dashed curve illustrates the ideal optical features of such a surface.

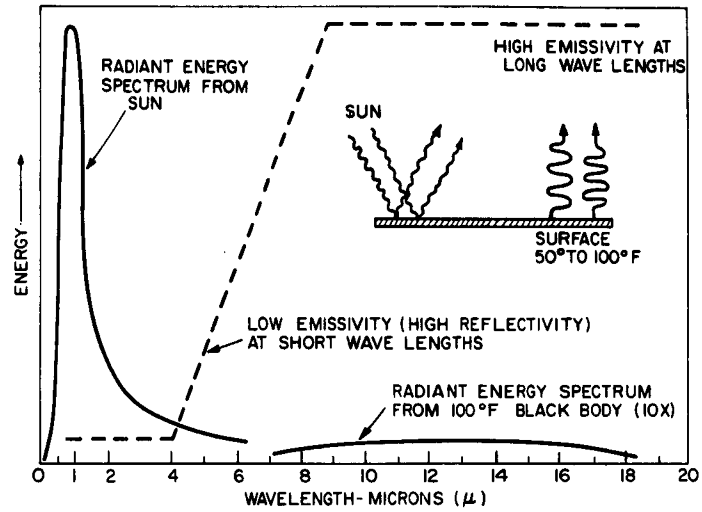

Fig. 9 - Energy balance involving absorption of short-wave radiation from the sun and emittance of infrared radiation from skin determines the temperature of satellite bodies. The dashed curve represents the surface optical characteristics required for developing desired surface temperatures.

The exact value of the ratio of solar absorptivity α to infrared–low temperature–emissivity ϵ determines the equilibrium temperature attained, as illustrated in Fig. 10. Ratios in the order of 0.1, as provided by a white painted surface, result in undesirably low temperatures. The high ratios provided by polished metal surfaces result in excessively high temperatures. Black, or oxidized gray surfaces provide for ratios close to one which are necessary for maintaining temperatures close to the normal ambient range. Actually, complications due to shape and orientation with respect to the sun dictate the use of striped or polka-dot patterns, illustrated in the figure. The relative area and distribution of such light and dark regions provide for developing of the desired temperature.

If very exact temperature control is required, it may be necessary to use active control systems. Such systems involve fan-like, shutter arrangements that open or close to present a dark or light surface in response to a temperature sensing device.

The Vanguard satellites had unique requirements involving high visibility from optical, ground tracking stations. This requirement for a shiny surface–high reflectivity–would have resulted in a very hot satellite. The solution in this case was to apply a thin film of silicon monoxide over a polished aluminum surface. Silicon monoxide is transparent to short wavelengths and is a highly efficient emitter at long wavelengths. Thus, a large fraction of the solar spectrum in the visible range–0.3 to 0.7μ–was reflected by the polished aluminum surface, transmitting through the transparent oxide surface. In turn, reasonably low temperatures were maintained by infrared emission from the silicon monoxide surface.

A satellite that revolves about the earth passes from the sunlight into the earth's shadow and back into the sunlight in periodic fashion. Such transients, or periods of 40 and 60 minutes for shadow and sunlight respectively, in the case of a near earth orbit, pose special problems of temperature control for passive systems. Compared to the face exposed to the sun, the earth-side face undergoes less drastic changes in temperature because it always sees a

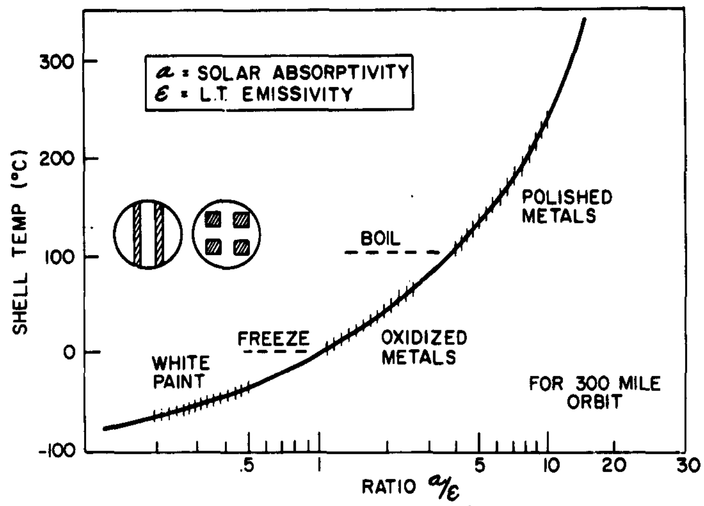

Fig. 10 - Temperatures developed by surfaces of various α/ϵ ratios

relatively warm earth. Spinning of satellite bodies serves to alleviate this problem; however, certain types of observation or communication satellites must maintain a fixed orientation to the earth that prevents the use of this technique. A full discussion of the temperature-control problem for all cases is outside the scope of this presentation. It should be obvious, however, that the problem of choice of materials for thermal control in space is primarily a question of optical properties of surfaces rather than of strength. Restrictions on weight dictate the use of light metals with special surface treatments.

The surface treatment problem is additionally complicated by the high vacuum and ultraviolet environment of space, that is destructive to organic materials such as the vehicles of paints used for striping. The effects of meteoric particles that may puncture the shell, and of high-energy charged particles that may sputter and erode the surfaces, are as yet poorly understood.

ROCKET PROPULSION REQUIREMENTS

Rocket motors may be designed for the use of either liquid or solid propellants. The liquid type consists of: (1) a combustion chamber, designed for the mixing and burning of the fuel and oxidizer; (2) separate tanks for storing the two liquids; and (3) either fast-acting pumps or a gas pressure tank to provide for high-pressure delivery of the liquids to the combustion chamber. The solid-type consists of a nozzle to direct the jet gases and a pressure vessel that contains the solid propellant and the high-pressure gases developed during the combustion. Both types require directional control systems entailing either jet deflector vanes or a gimbal mount for the nozzle.

The index of merit for a rocket motor is the specific impulse value (I_s) that is determined primarily by the combination of oxidizer and fuel used for the propellant. The I_s value relates to the pounds of thrust produced per pound per second of propellant consumed. The attainment of high specific impulse requires propellent combinations that produce the highest possible jet velocity. In turn, this requires maximizing the combustion temperature and minimizing the molecular weight of the combustion products. These relationships may be expressed as follows:

$$I_s = \frac{\text{lb (thrust)}}{\text{lb/sec (propellent consumption)}}$$

$$I_s = kV_{jet}$$

$$V_{jet} = k\frac{(\text{gas temp})^{1/2}}{(\text{gas mol wt})^{1/2}}.$$

The highest values of I_s for chemical combustion are obtained by the use of hydrogen in combination with oxygen (LOX) or fluorine. The I_s values for these exotic fuels are in the range of 375 to 400 as compared with 250 to 275 for conventional fuels such as LOX and hydrazine. To attain higher I_s values it is necessary to use nuclear rockets, consisting of an assembly of hot fuel elements over which is passed a low molecular-weight gas, such as hydrogen. The hot stream is then expanded through a nozzle to provide the thrust. Hydrogen, heated by fuel elements operating at approximately 5000°F, the highest feasible temperature of operation, may provide I_s values in the order of 1200. In other words, such a nuclear rocket may provide three times the thrust per pound of propellent that is theoretically possible for chemical rockets and four times that of present-day chemical rockets. The importance of I_s, as related to payload and to final velocities attainable by rockets for satellite boost, is discussed in relation to construction features.

Cooling of liquid motor systems is generally accomplished by regenerative methods, as illustrated in Fig. 11. Basically, this involves passing the fuel or oxidizer through a double wall or tubing structure surrounding the chamber, prior to exit into the chamber. Such methods are possible because of the large volume of fuel that is burned in a relatively short time. High-temperature gradients are developed between the flame wall and the coolant passage wall, as illustrated. The double-wall construction often poses complicated hydraulic problems, involving channeling of the flow, with the result that, in some regions, the liquid may overheat and produce boiling. This event results in a reduction of heat-transfer rates and immediate heating of the wall to melting. It is possible to construct such motors with aluminum, at least for the cases involving lower flame temperatures. For high flame temperatures and high pressures, stainless steel is adequate, if high flow rates are maintained. While design may be critical for such motors, particularly in the throat region, there does not appear to be basic materials limitations due to temperature. Difficulties may arise, however, from corrosive attack, particularly for exotic combinations of oxidizers and fuels, such as fluorine.

The combustion temperatures of solid-propellent fuels are in the range of 4500° to 6500°F. Two general types of grains are used: a solid grain that burns progressively from one end–cigarette burning–and a scalloped, perforated grain that burns from the center radially to the circumference–star grain. The nozzle throat for solid-propellent motors provides severe thermal problems and, additionally, is subject to enlargement by abrasion due to the high-velocity exit of solid combustion products. Such enlargement is undesirable because it changes the thrust of the motor during flight.

Figure 12 illustrates six basic types of solid-propellant rocket nozzles. The simplest design (type 1) suitable for short burning times in the order of 3 to 6 seconds, consists of a thin steel wall. By coating with ceramics, such as flame-sprayed alumina or zirconia (type 2), a thermal lag is developed that may potentially double the allowable burning time. Designs, suitable for burning periods ranging from 20 seconds to approximately 1 minute (types 3 and 4), require the use of refractory materials and steel as combination heat sinks. The simplest designs utilize conventional graphite and are particularly useful for propellents having flame temperatures not exceeding

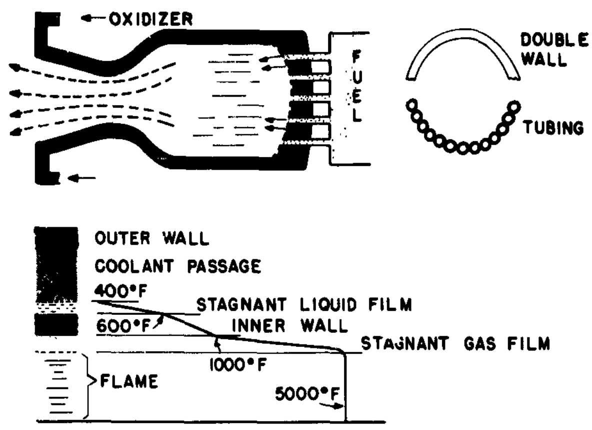

Fig. 11 - Regenerative cooling features of liquid-propellent nozzles

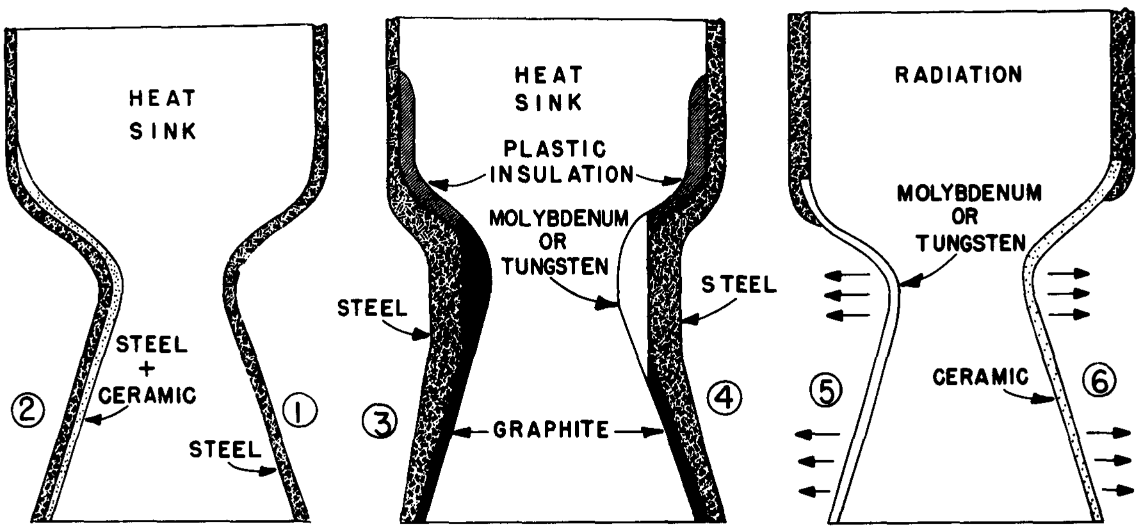

Fig. 12 - Construction features of solid-propellent nozzles

approximately 5000°F. As the flame temperatures are raised to 5500°F, the use of conventional graphite becomes marginal, restricting the time of operation and necessitating a change to molybdenum or in special cases to tungsten. Such composite nozzles are very heavy, because the large amount of heat that must be absorbed by the wall in order to prevent melting, requires a high heat-sink capacity system. This capacity is obtained by the use of walls of 1 to 2 inch thickness. The long burning times of such rockets also requires the use of thermal protection for the base of the chamber. Plastic insulation in the form of phenolic fiberglass laminates provides a simple and effective solution to this problem.

Burning times extending to several minutes are possible only for high-altitude rockets, such as the final stages of satellite-launching vehicles. Such rockets operate at very low chamber pressures because of the low back pressures. Burning rates are designed to be very low, and the thrust time accordingly can be extended to possibly as high as 3 to 4 minutes. The use of heat-sink solutions for firing periods of this duration is prohibitive because of stringent weight limitations for final stages. The only practical designs (types 5 and 6) would seem to require the use of radiative cooling principles, involving ceramic or refractory metal construction. Such nozzles may be relatively thin-walled because of the low back pressures required at very high altitudes.

Procedures for varying the direction of thrust in solid-propellent motors generally depend on a deflector device, such as vanes in the center or sides of the jet stream; obviously, this is a most demanding service for materials. Consideration of the temperatures involved, suggests the use of graphite for low flame temperatures and short firing times, and either molybdenum or tungsten for more severe conditions of temperature and time.

All of the large, first-generation, satellite boosters are based, at least for the first stage, on liquid propellent rocket motors. In view of the complexity of such systems, and the reported high reliability of solid-propellent motors, one may wonder why the solid-propellent rockets were not used intially. While solid-propellent rockets have distinct advantages of simplicity, they also have distinct disadvantages. The payload capabilities of solid-propellent rockets have been inferior to that of the liquid types because of lower I_s and higher metal parts weight. Another drawback is the difficulty of varying the thrust.

MASS RATIO FACTORS

The final velocity attained by a satellite or escape vehicle depends on the I_s of the rocket motor and the ratio of takeoff weight (W_i) and <u>all up</u> or final weight at burn-out (W_f).

$$V_{burn\text{-}out} = I_S \, g \, \ln \left(\frac{W_i}{W_f}\right)$$

where W_i/W_f is the mass ratio. The relationships of these factors is illustrated in Fig. 13. For simplicity of presentation, the mass ratio is expressed in terms of the propellent fraction, i.e., the fraction of the rocket weight represented by the propellent. The remainder is the sum of the weights of the inert parts of the rocket and of the payload. The structural significance of the propellent fraction term may be better appreciated by comparison to content fractions of common packaged items. By such comparisons, conventional construction may be described as a proportion of inert components weight to propellent weight which is equivalent to that of the can to the contents of canned foods. The proportions for advanced construction compares to the relationship of the eggshell weight to the content weight. The attainment of such extreme construction efficiency presents serious problems in fabrication and in selection of materials.

The relationships presented in Fig. 13 indicate that, with "conventional" construction, the final velocity attained (for a single-stage rocket) is in the order of 1.5 times the jet velocity. For highly-advanced rockets, having propellent fractions of 0.90–mass ratio 10–it is possible to attain final velocities in the order of 2.25 times the jet velocity. It may be noted that, for conventional fuels, a single-stage rocket of conventional construction–0.85 propellent fraction–attains a burn-out velocity in the order of 8500 mph. By using the most efficient propellent combination (H_2–F_2) and a 0.90 propellent fraction construction, it is barely possible to attain earth orbit velocities–18,000 mph–with a single stage. Single-stage nuclear rockets may provide for either earth-orbit or escape velocities–25,000 mph–with conventional construction, depending on the operating temperature of the reactor.

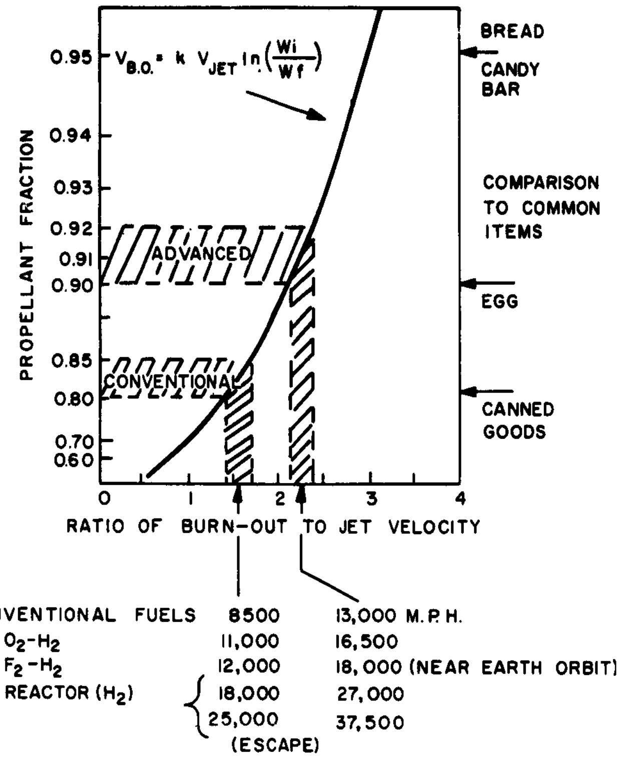

Fig. 13 - Relationship of propellent fraction to the relative burn-out velocity of single-stage rockets. The burn-out velocity also depends on the jet velocity of the particular propellent, as indicated.

In order to attain high velocities with conventional propellants and conventional construction, it is necessary to use staged vehicles. By using several stages, it is possible to attain a final velocity in direct proportion to the number of stages. In other words, for equivalent construction and the same I_s—same propellent—for each stage, a third stage would have a final velocity three times that of a single stage. Thus, three stages of conventional fuel and conventional construction rockets are required to attain escape velocity for the final stage. The same performance may be obtained by a two-stage rocket featuring conventional fuels and advanced construction. These comparisons relate to essentially zero payload weights; as payload is added, the final velocities that are attained are greatly decreased, requiring the use of additional stages. The penalty for obtaining earth orbit or escape velocities by staging of inefficient rockets is that the payload becomes very small, because each stage, in turn, becomes the payload of the previous stage. Thus, for a 0.90 propellent fraction, three-stage system, the final weight that is accelerated to escape velocity becomes 1/10 x 1/10 x 1/10 or 1/1000 of the takeoff weight.

A single-stage nuclear rocket may be expected to place "all up" weights in earth orbit or escape, of 10 to 40 percent of the takeoff weight, depending on the operating temperature of the reactor. Figure 14 illustrates the approximate relationship between "all up" weight in earth orbit, to propellent weight, for I_s values ranging from those of conventional fuels to those of hydrogen propellent, hot wall reactors. If 4000°F is taken as a practical limit for operation of hot wall reactors, it may be deduced that a 40 percent payload and structure weight may be placed in earth orbit by a single stage, as compared with 1 to 2 percent for a two-stage rocket of advanced construction, using advanced types of conventional fuels (I_s = 250 to 275).

A single-stage, exotic fuel rocket is represented as delivering approximately 10 percent structure and payload in orbit. These comparisons highlight the importance of nuclear rockets for purposes of placing large payloads in earth orbit. The feasibility of such systems depends on the development of moderator and fuel element materials that would permit reliable construction of approximately 400°F hot wall reactors. In order to attain such temperatures it is necessary to use graphite or carbide moderator materials and uranium carbide fuels. The principal problems involve the reliability and stability of these materials under conditions of severe thermal stresses and in an environment of hydrogen.

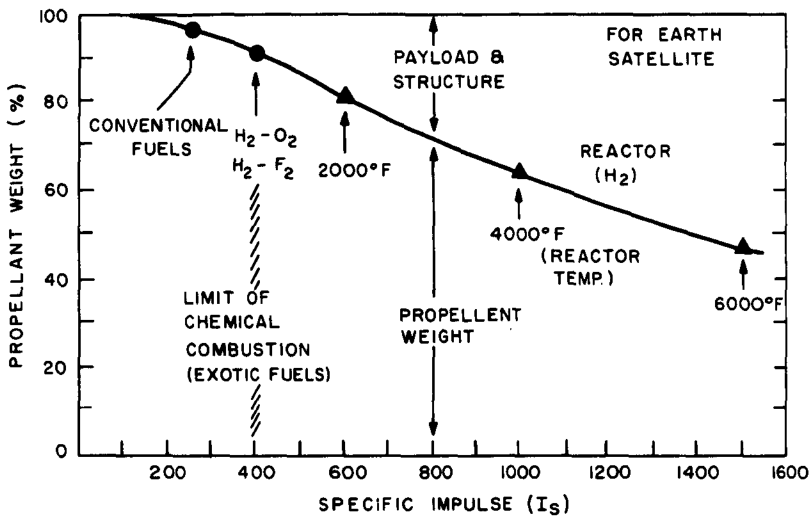

Fig. 14 - Relationship of I_s capabilities of various rockets to percent of launch weight that may be placed in earth orbit

ROCKET MOTOR CASING CONSTRUCTION

The importance of reducing inert-parts weight to the minimum for the case of solid-propellent ballistic missiles may be illustrated in terms of range loss due to excess inert-parts weight. For example, let us assume that a two-stage IRBM missile is optimized to 0.92 propellent fraction construction and that, for the particular propellent I_s, the design results in a range of 1500 miles. Range equations provide for calculating the loss in range resulting from a decrease in the propellent fraction by the addition of inert weight, as follows:

Reference	Range
Optimized condition	1500 miles
300 pounds added to first stage	Approximately 1450 miles
100 pounds added to second stage	Approximately 1430 miles
200 pounds added to second stage	Approximately 1350 miles
300 pounds added to second stage	Approximately 1250 miles

The implication of these figures is that the inert-parts weights of the second stage are much more critical than those of the first stage.

The requirement for reducing the inert-parts weight to an absolute minimum has focused attention on the weight efficiency of materials used for nozzles and for the casing. At the present stage of development, the potential weight reductions for first-generation systems are greater for nozzles because of the very heavy heat-sink materials used for these components. While the potential weight savings for the casing are less than for the nozzles, it is essential that materials of the highest possible strength-to-density ratio be used in order to maximize range. The casings for ballistic missiles actually are thin-walled pressure vessels, varying from 4 to 6 feet in diameter and with wall thicknesses in the order of 0.050 to 0.150 inch, depending on range and on the stage in question. Early attempts to produce such casings centered on the use of steels having yield strengths in the order of 230,000 to 250,000 psi. Unfortunately, such steels are highly sensitive to the presence of minute imperfections or notches, resulting in the development of brittle fracture–shattering–when pressurized to stress levels in the order of 50 percent or less of the yield strength of the material. The design pressures generally involve attaining stresses in the order of 95 percent of the yield strength. Therefore, the failures occurred at stresses that would be tolerable by notch ductile steels of lower yield strength, and no advantage was gained by the use of the higher strength materials. It now appears that a yield strength barrier exists, such that all known steels that are heat treated to yield strengths in excess of approximately 200,000 psi are excessively notch sensitive for use as welded pressure vessels. Metallurgical research may show that this barrier level may be raised, however, this is not certain. Inasmuch as the important parameter is the yield strength to density ratio, attention is also given to titanium alloys that are competitive with high-strength steels because their lower yield strength is offset by the lower density of titanium.

Presently, there are three widely divergent philosophies on fabrication procedures that are required to ensure a combination of minimum weight and maximum reliability for rocket casings.

Perfection Construction Using Brittle Steels

This approach is based on a concept of fabrication by shear forming, spinning, or cold drawing so as to develop a weld-free, one-piece construction. It is argued that the elimination of all flaws due to welds, and the use of metal sheet of perfect quality–no inclusions or notches–should permit utilization of notch-brittle steels of the 230,000 to 250,000 psi yield strength class.

Flaw Size Control for Roll-Weld Construction

This approach is based on a concept of restricting the size of largest flaws–by inspection procedures–to that which would not result in enlargement and propagation of a tear or brittle fracture, for the particular service stress level. For steels of the 190,000-psi yield strength level and service stresses near the yield strength, the allowable flaw sizes are quite small and close to the limits of detectability by reliable inspection procedures. The postulated balance between allowable stress level and allowable flaw size that is the essence of this concept, naturally directs this approach to obtaining maximum performance by refinements in flaw inspection procedures and by exacting stress analysis.

Elimination of Welds at Critical Positions

This concept is considered a practical approach to perfection construction. In practice, it is based on using notch ductile steels–190,000-psi max yield strength–and eliminating welds from positions marked X as illustrated in Fig. 15. Forging or shear forming processes are used to produce short cylinders that are welded together to form the body. This procedure

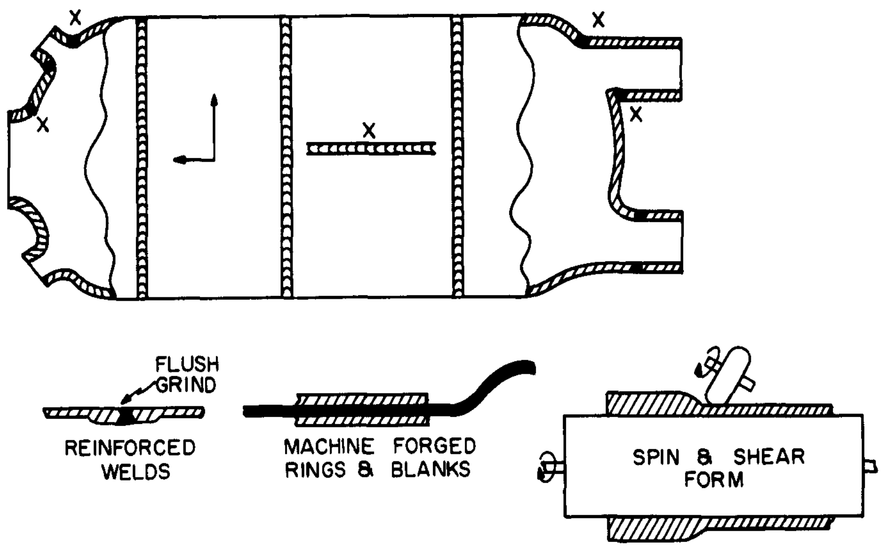

Fig. 15 - Idealized representation of a solid-propellent rocket motor casing, illustrating an advanced form of construction based on the elimination of welds (X) from critical positions. Other features include machining of components from forged blanks, shear spinning or forging of components, and weld reinforcement.

eleminates welds in the longitudinal–high stress–direction. The head closures are forged so as to provide integral port openings, thus removing welds from regions of high stresses and bending movements. In essence, perfection construction is used only at the critical positions. Additional precautions may be taken by machining the ring forgings so as to provide reinforcement for the girth weld regions, and thereby reducing the stress level normal to the weld direction.

The concept of perfection construction utilizing notch brittle steels as discussed above, is generally considered visionary. Consideration of possibilities of accidental introduction of notches–scratches would be critical–and of stress corrosion cracking, etc., in storage, provide additional arguments against the feasibility of such an approach, if high reliability is required.

Systems that are expected to be operational in the near future are based on either the roll-weld construction with flaw-size control (item 2) or the semiperfection construction (item 3) based on eliminating welds from critical positions. In all cases, the steels used are restricted to the notch ductile variety. At the time of this writing, the crucial question regarding the merits of these two approaches involves the relative reliability of the roll-weld, flaw-size controlled casing in comparison to the inherently more reliable but also more expensive semi-perfection construction casing.

It should be noted that range and reliability trade-offs are involved. A construction that consistently demonstrates capability of withstanding hydrostatic testing to above yield point pressures may logically be considered capable of reliably withstanding near yield point stresses in service. Conversely, a construction that indicates propensities for hydrostatic test failures at near yield point pressures may logically be suspect. Such performance should naturally force a reduction in the allowable service stress level that translates to higher casing weights and reduced range. Because of the large number of casings that are scheduled for fabrication and testing, it is expected that the relative merits of the two competing approaches will be resolved undisputably by failure statistics.

DIRECT ENERGY CONVERSION

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ABSTRACT

The important problem of improved power sources for both military and industrial requirements demands an aggressive effort in order to develop direct conversion processes. Of the several processes possible no one process is expected to provide a panacea, but solar cells, thermo-electricity, thermionic emission, and fuel cells are all expected to be useful according to their individual characteristics. In each case there are important materials problems which will determine the ultimate success of the development. Particularly, the field of high-temperature semiconductors must make great strides to meet the requirements of these advanced power sources.

* * * * *

Improved power source and energy-conversion systems represent one of the most important long-range scientific problems facing the nation. A rapidly increasing population and an increasing per capita usage of energy, coupled with declining fuel reserves, poses a problem of serious proportions. The single requirement of making sea water potable for a greatly expanded population will consume vast quantities of energy. Utilization of ever poorer ores will impose a continually increasing demand on energy sources. Space exploration consumes energy at fantastic rates, and the race for space domination will unquestionably be won by the nation who can best provide the energy requirements. A strong case can in fact be made that the strength of any economy depends on the ability to provide energy for its population.

The military services have difficult, immediate problems which require new power systems, and part of the efforts to solve these problems is represented by the research and development program on direct conversion. Navy requirements can be catalogued in three general areas of usage: flight vehicles, both air and space; remote locations, including portable power and unattended sites such as underwater installations; and shipboard power, both for propulsion and for auxiliary uses.

Each of the three areas of usage involves unique requirements. For space vehicles, for example, weight is a prime consideration. The pounds per kilowatt is more important than efficiency per se. In unmanned vehicles freedom from maintenance is an additional necessity. For remote locations, freedom from maintenance is again the primary requirement. For shipboard use, silence is an important consideration, together with space, weight, and efficiency. Again, reliability and low maintenance are important elements in the choice of a power system. For all of these requirements, various kinds of direct conversion processes deserve investigation.

Research on direct conversion is directed primarily toward utilization of nuclear energy. The same conversion processes, however, work equally well with other sources of energy; for any particular application, all possible combinations of energy sources and conversion processes need to be examined.

We are concerned, therefore, with utilizing all three fundamental sources of energy: (a) solar energy, both in the form of radiation and absorbed as heat; (b) chemical energy, primarily as the combustion of fossil fuel, but also as electrochemical reactions; and (c) nuclear energy, producing heat from the decay of isotopes or from fission processes in reactors and, ultimately, from fusion.

Before discussing the conversion processes, it may be helpful to define direct conversion. A reasonable statement is that direct conversion includes any process in which energy is not transferred to a secondary working fluid. Thus, a combustion engine in which heat expands a vapor which pushes against pistons, or a turbine in which gas or steam works against blades, is obviously not direct. Magnetohydrodynamics could be challanged because it employs a working fluid, though in most systems the expansion and subsequent pressure drop of the plasma are not the heart of the process and for convenience it is normally regarded as direct conversion. Thermionic emission and thermoelectricity are clearly direct conversion. Direct collection of charge from the various particles in nuclear reactions would admittedly be even more direct, but many suggestions for such processes have been carefully examined, and none of them look even remotely promising.

Four energy-conversion processes are receiving the majority of attention: photovoltaic cells, thermoelectricity, thermionic emission, and fuel cells. Other possibilities exist such as magnetohydrodynamics, which, to become feasible, must wait for the solution of extremely difficult high-temperature-materials problems. Pyroelectricity, Curie-point inversions, and several others could be mentioned, but they all appear to have serious limitations except for special applications. Those which look immediately promising are the first four listed.

The most highly developed today are the solar cells utilizing energy in the form of radiation. In the most familiar form, a very perfect silicon crystal is treated with traces of impurities that introduce extra positive and negative charges on the two sides of a thin wafer (Fig. 1). These extra charges remain on their own side of the junction that separates the two sides until light energy strikes the crystal. This radiant energy further disturbs the electrical balance of charges and starts them moving toward the surfaces and the junction. This current flow then continues as long as light strikes the crystal.

The physics of this process is reasonably well understood, and the theory tells us that as much as 25 percent of the incident radiation can be converted to electricity, under special conditions possibly as high as 40 percent. The best now reported from the laboratory is 14 percent, and substantial production quantities can be obtained that give a 10 percent conversion efficiency. The cells are reliable and operate indefinitely with no loss in efficiency.

These represent the best available means of providing small amounts of power for satellite communications. The cells last so long, in fact, that a time switch must be incorporated to shut-off transmission after the desired interval. They are limited to small power supplies, however, because of their weight. Bare cells produce only three watts per pound. In a satellite, they must be distributed over the surface of a free-tumbling sphere or a mechanism must be provided to keep them pointed at the sun. A third possibility is to use the solar cells to charge batteries, which in turn provide current during dark periods. All of these schemes add

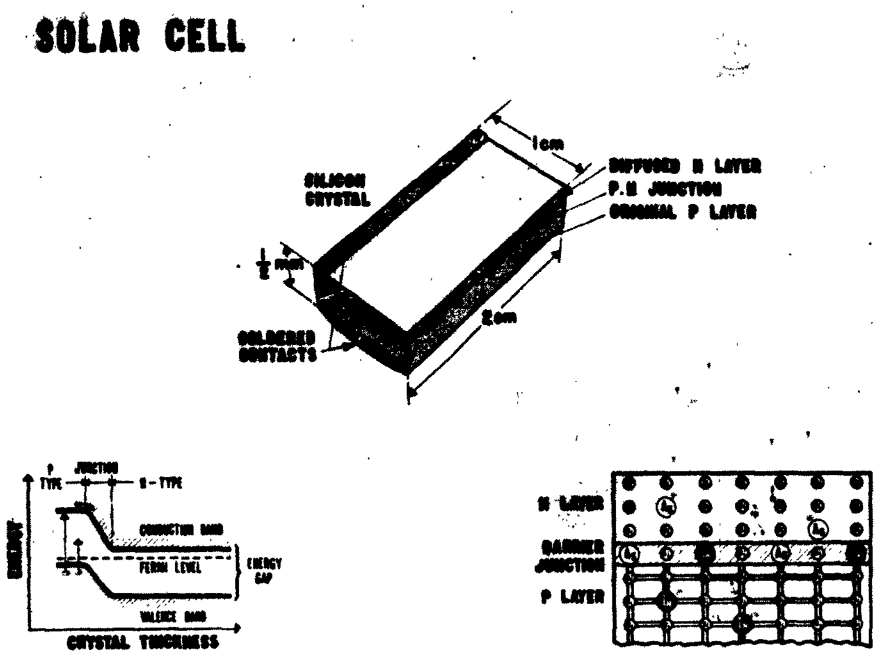

Fig. 1 - Solar cell

weight so that the complete power package delivers less than one watt per pound. Stated in another manner, the power supply weighs more than 1000 pounds per kilowatt and this is far too heavy to boost into space.

As large power supplies for ground stations, solar cells have a problem of size and cost. A ten-kilowatt generator suitable for a modern-home power supply, for example, would occupy 100 square yards and cost $2,000,000.

Like all the direct conversion processes, the problem is primarily one of improved materials. Most of the research effort is directed toward improved efficiency by growing more perfect crystals and by experimenting with different materials such as thallium arsenide and cadmium sulfide. Some increased efficiency can be expected but probably by no more than a factor of two. For space applications it would appear more profitable to attack the weight problem directly because the active region of the crystal is only a few millionths of an inch thick, a tiny fraction of the total thickness of the present wafers. There appears to be much room for improvement by using crystals in the form of thin films, and substantial improvements must be made for solar cells to remain competitive as other devices are developed. The best projection using existing solar cell techniques predicts 120 pounds per kilowatt, which is still much too heavy.

Another method for the utilization of solar energy is by collecting it and absorbing the heat content. For example, a mirror could be employed to collect and focus the sun's energy into a metal cylinder, where the concentrated heat could be used to operate thermocouples or thermionic diodes (Fig. 2). In this instance heat would flow from the hot interior of the cylinder through the energy conversion device creating electricity, and the waste heat would be radiated into space, or in the case of a ground installation it would be discharged into a body of water.

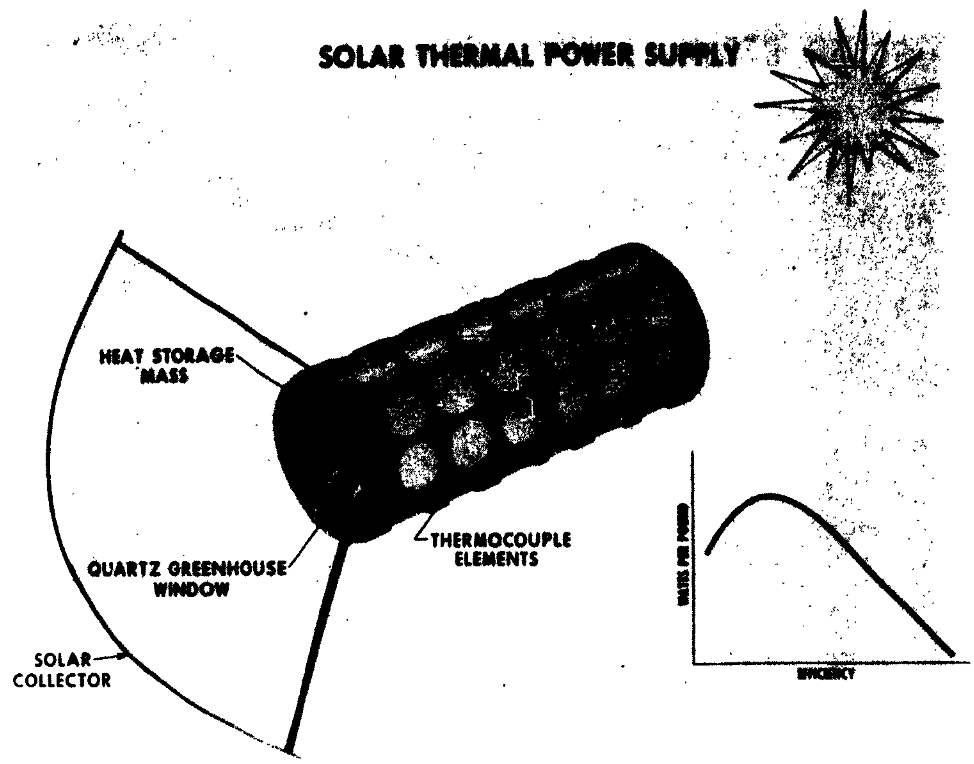

Fig. 2 - Solar thermal power supply

The heat-conversion process which is receiving most attention at the present time is thermoelectricity. This is basically a very simple phenomenon (Fig. 3). If a temperature difference is maintained across any bar of a material which conducts electricity, the electrons at the hot end of the bar move about more vigorously and tend to drift toward the cold end. It is entirely proper to say that heat pushes electricity through the bar. In some materials it is negative charges that move and in other materials the positive charges move. These opposite effects can be added together when the two types of materials are properly selected and joined to form a thermocouple.

This is a very old process. It was discovered in 1822 and efficiencies as high as 3 percent could be obtained in 1850. This was a higher efficiency than was obtained by the steam engines of that day. The scientists involved took a wrong turn, however, and no further progress was made, except that thermocouples have been widely used to measure temperature. Research in physics has recently taught us that to produce substantial amounts of power by the thermoelectric process, metals which were the materials formerly used in thermocouples were the wrong materials. Metals have so many free electrons that increasing the temperature simply causes them to become more crowded with little chance to drift. It is now recognized that semiconductors such as lead telluride which have much smaller numbers of free electrons but with more freedom to drift can produce substantially larger voltages and currents.

The physics of thermoelectricity is now reasonably well understood, and the theory indicates that efficiencies as high as 35 percent to 50 percent might be achieved. To accomplish this the materials must have precisely the optimum set of properties in the face of a number of conflicting requirements. As previously stated, the number of free electrons must be small in order to generate a large voltage. But the number of electrons must be large enough to avoid losses from internal resistance, which generates heat that flows in the wrong direction. And finally, the material must have a low thermal conductivity so that heat cannot flow through the material without doing some electrical work. The optimum compromise that must be reached is shown in the lower left diagram of Fig. 3.

Fairly sophisticated guide lines have been developed for these materials requirements. By following trends that have been established relating the periodic behavior of elements and compounds together with symmetry considerations to established transport properties, preferred families of chemicals can be selected for investigation. As indicated in Fig. 3, the optimum properties occur with 10^{19} free electrons per cubic centimeter, which means a material very nearly but not quite metallic. The requirement is thus for a semiconductor not quite degenerate, with a band gap sufficient so that intrinsic carriers are not formed at the operating temperature, in order to avoid ambipolar complications. The additional difficult requirement of a low thermal conductivity is less well understood, but it is related to anharmonicity in the lattice such as occurs in defect structures and in crystals with a large difference in the atomic weight of adjacent atoms.

To complicate the situation further, each of these important properties of the material changes with temperature so that for any given material the best compromise of properties will exist for only a small temperature range. A thermocouple is a simple heat pump and, like all other heat engines, the efficiency increases with larger temperature differences. To operate over a wide temperature range requires, however, a number of materials each efficient in its small temperature region. The several materials can be put in series as shown in the upper left diagram of Fig. 3 and perform much like the stages of a turbine. This requirement for using several different materials in the same thermocouple, including some that operate at high temperatures, makes the development difficult and expensive. Progress, nevertheless, is excellent. The program is now barely started and a conversion efficiency of 10 percent can be readily obtained. If a fuel burner is used as the source of heat, however, half of the total heat goes up the chimney so that the overall efficiency of the system is reduced to 5 percent. The present weight is about 65 pounds per kilowatt, and a design for a space power supply indicates the possibility of 5 pounds per kilowatt.

Using thermocouples with nuclear heat is a promising possibility. By surrounding an isotope capsule with thermocouples, nearly all the heat generated can be captured to yield an electrical output of 10 percent or better with today's materials. The present design concept for using thermocouples with reactors involves circulating the primary coolant through a heat exchanger containing the thermoelectric materials, as shown in Fig. 4. No experience is available on which to base a predicted efficiency but it is reasonable to expect that the heat losses would be substantially smaller and the efficiency therefore higher than with a fuel-fired thermoelectric system.

The thermocouples would be placed in the cooling loop in present designs to protect the materials from radiation damage. It is intended ultimately to use the thermoelectric elements in the pile as sandwiches immediately adjacent to the fuel as shown in Fig. 5. There are, in fact, possible fuel materials such as uranium and thorium sulfides which are themselves semiconductors and therefore potential thermoelectric elements. There must be a great deal more study of radiation damage, however, before such a system can be seriously proposed. Although very early results are encouraging, they are by no means sufficient to indicate any kind of conclusion.

The process which does lend itself readily to incorporation in the pile is thermionic emission. This, too, is basically a simple process, and it is based on a discovery by Thomas Edison (Fig. 6). At one period early in his manufacturing of light bulbs, he had two independent filaments in the bulb, only one of which was connected at a time. After the first filament burned out, the bulb was turned around in the socket so that the spare filament was connected. In

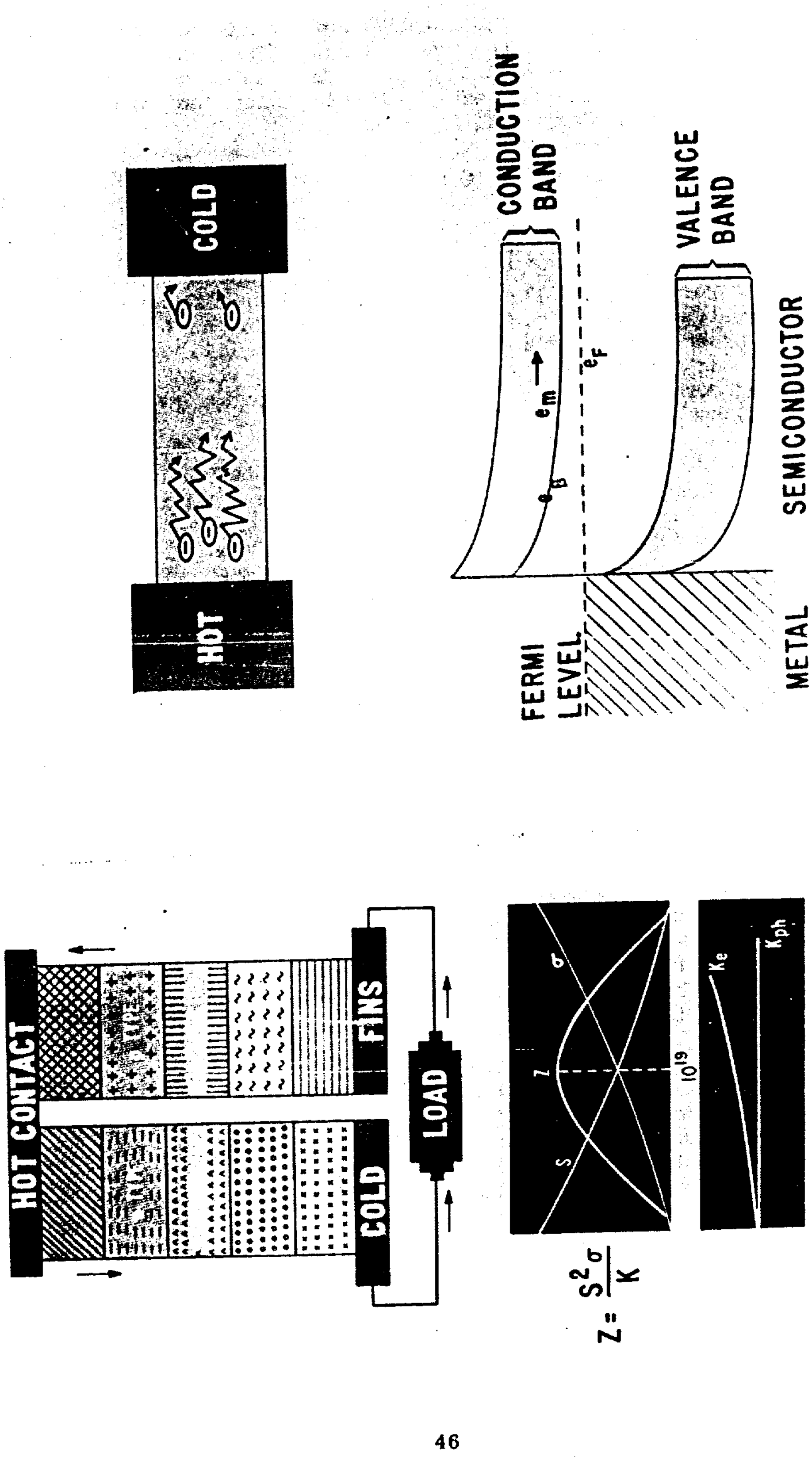

Fig. 3 - Thermoelectric effect

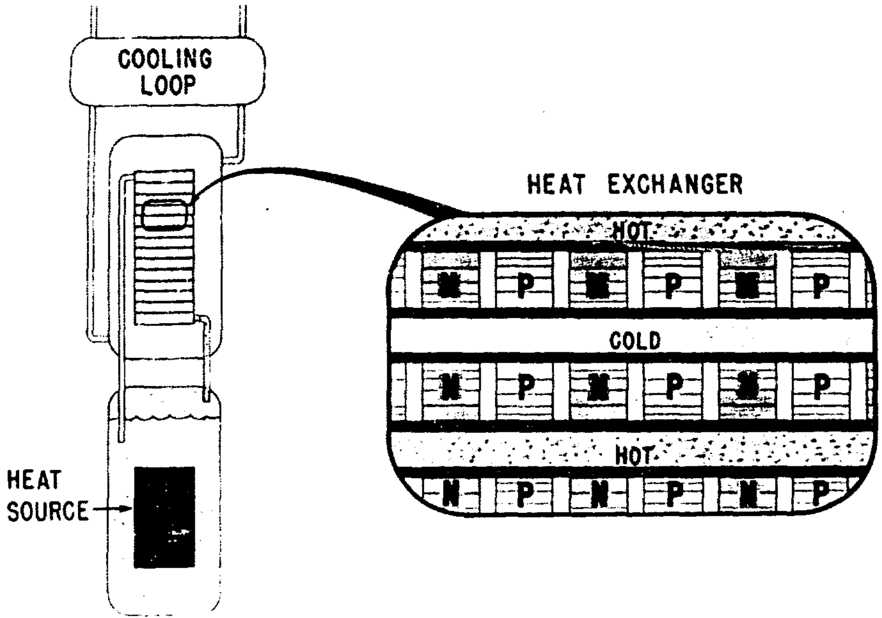

Fig. 4 - Thermoelectric power source

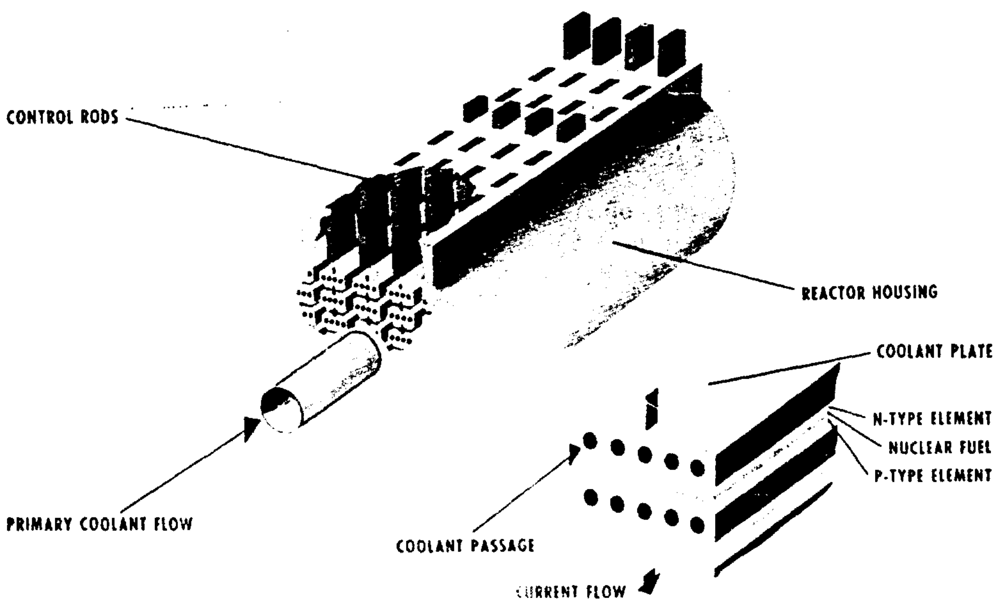

Fig. 5 - In-pile thermoelectric generator

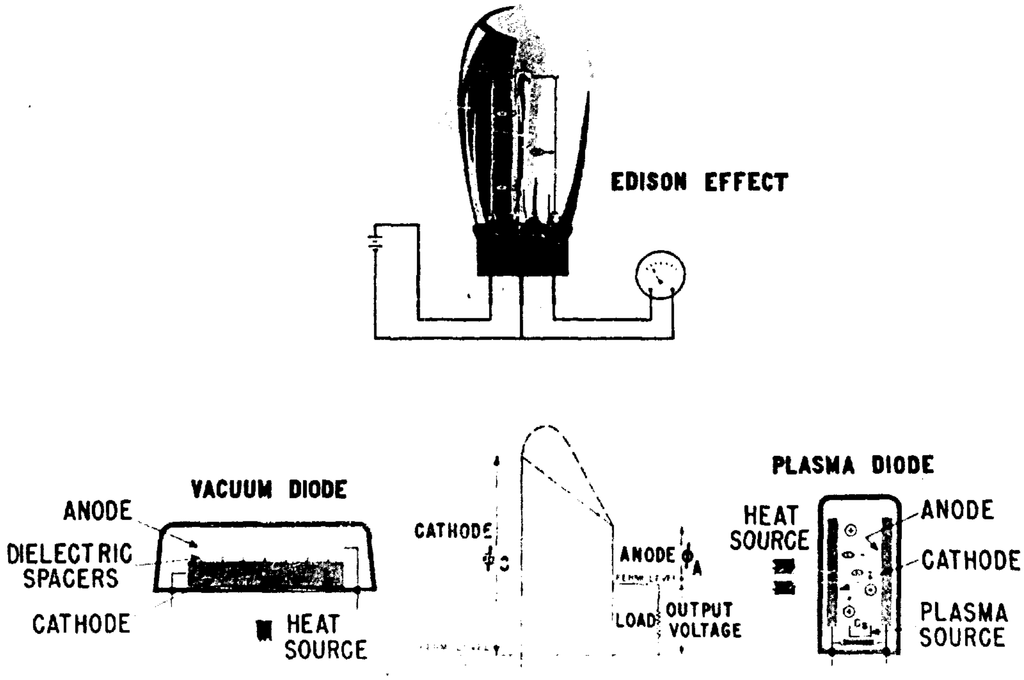

Fig. 6 - Thermionic emission

testing these bulbs Edison discovered that he could draw a small current from the filament that was not connected. Some electricity was moving through the vacuum in the bulb from the hot filament to the cold. This is the basis on which all radio tubes operate, and the same process now promises to become an efficient energy converter.

To generate substantial amounts of power by the thermionic process, it is necessary for large numbers of electrons to flow from the hot cathode to the cold anode. Because the electrons are all negatively charged, they repel each other and build up a charge that limits further flow. This problem can be minimized by putting the cathode and anode very close together, as shown in the bottom left diagram of Fig. 6. The spacing required, however, is less than a ten thousandth of an inch, which is virtually impossible to keep uniform between two surfaces over a large area, particularly at high temperatures.

Another way to minimize the space charge is by introducing an ionized gas as shown in the bottom right-hand illustration of Fig. 6. Positive charges on the gas plasma neutralize the negative electron charges and permit the current to flow. Calculations indicate that the process could have a theoretical efficiency of 40 percent or higher. Efficiencies of up to 13 percent have been demonstrated for brief periods in the laboratory, but enormous difficulties appear in producing a useful, long-lived device. The best that is available today is a small close-spaced diode with an efficiency of 2 percent.

The materials problems are particularly difficult in this case because of the high cathode temperature, together with the corrosive nature of cesium gas which is the most easily ionized plasma. Tungsten and tantalum metals have received the most attention, but a substantial number of carbides, nitrides, and other refractory compounds are under investigation. Even when the development of long-lived cathodes has been accomplished, serious materials problems will remain in connection with structural parts, particularly seals which are resistant to the cesium corrosion. The behavior of the plasma itself also presents some formidable problems; the potential advantages of thermionic emitters justifies an agressive effort to overcome difficulties.

The diode is potentially the lightest weight of all energy converters. Design projections indicate less than one pound per kilowatt which would make them the obvious choice for space vehicles. The biggest advantage, however, is the simplicity of the in-pile converter. The fuel rod itself acts as the cathode and the can acts as the anode (Fig. 7), and very little else is involved. When efficiency and long-lived reliability are achieved, this will certainly be the most simple of the nuclear energy converters.

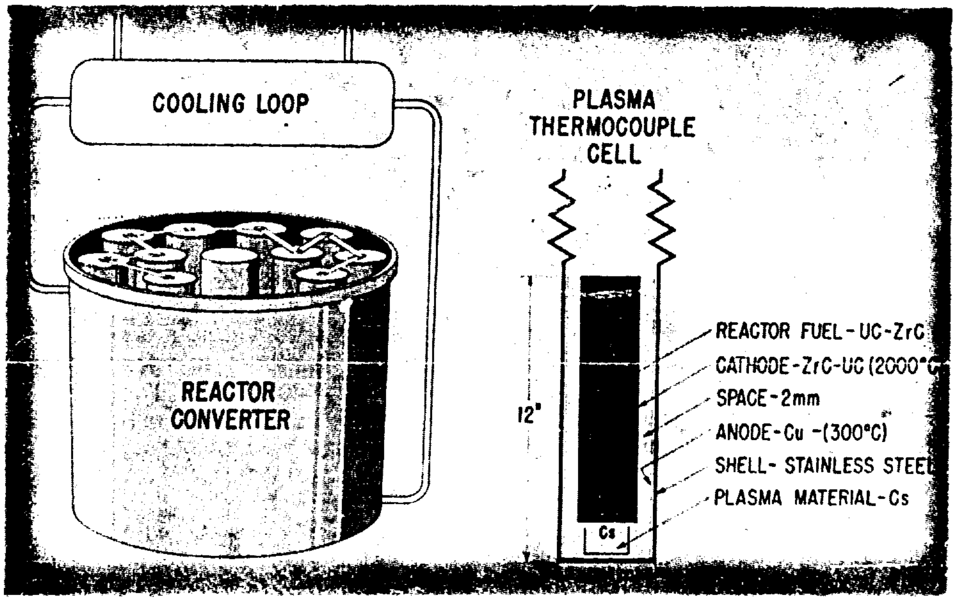

Fig. 7 - Nuclear thermionic converter

For high efficiency, however, the continuous-feed fuel cell is the most promising device. Unlike the thermocouple and the diode, the simple fuel cell is not a heat engine. It is a battery and is limited only by chemical reaction principles, in which two chemicals are fed into a cell where they react and produce an electric charge and a chemical by-product. Theoretically, this can approach 100 percent efficiencies, and as high as 90 percent has been demonstrated under special laboratory conditions. In the most simple form (Fig. 8) hydrogen and oxygen gas are continuously fed through porous carbon rods and react in an electrolyte to form electricity and water. Such cells have operated continuously for five years at low output levels but develop problems as output levels are increased. The space required to store hydrogen limits the value of these cells for shipboard and space vehicle uses, but many other applications look promising.

Dozens of variations of fuel cells exist utilizing a variety of chemicals. The most exciting possibility is a fuel cell which would use conventional petroleum products and air as the fuels; and several companies have such cells in early stages of development. The general scheme is to use catalysts in the electrodes which would separate hydrogen from the hydrocarbons, with oxygen from the air as the other fuel. Such cells have been demonstrated with efficiencies of

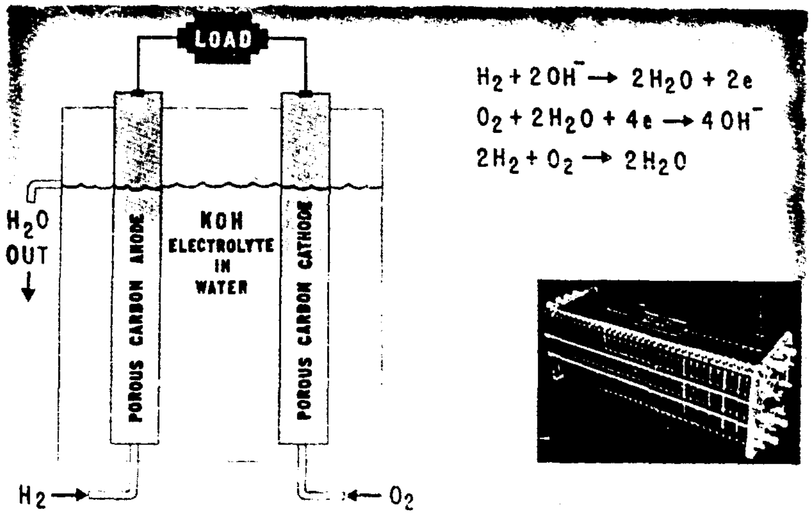

Fig. 8 - Hydrox fuel cell

better than 35 percent at low temperatures and up to 75 percent at higher temperatures. The problem is to keep them operating at high output levels for long periods without having impurities poison the catalysts, thus reducing the efficiency. The weight is not especially good on a pound per kilowatt basis (perhaps 80 lb/kw), but weight per kilowatt-hour of the cell, plus its fuel, is about twice as good as a conventional power plant plus its fuel because the higher efficiency all uses less fuel.

Success in these devices could obviously have a large impact on the whole problem of power supplies. An efficiency of 60 percent to 80 percent is a very reasonable goal and could result in doubling or tripling the life of our fossil fuel reserves.

Again, however, there are formidable materials problems. A high-temperature hydrox cell has failed through years of development to realize its potential primarily because of difficulties with sintered nickel electrodes. Containment materials for high-temperature acid reaction media are a limitation in the hydrocarbon cells. Even the porous carbon electrodes for low-temperature hydrox cells are far from perfect; a substantial materials development effort is justified by the promise of the device.

Fuel cells can also be operated as closed cycles activated by nuclear heat. The chemicals formed by the battery action could be decomposed by heat to reform the original chemicals used in the fuel cell and recirculated indefinitely (Fig. 9). This is a heat engine again, however, limited to less than 35 percent efficiency, and the advantages over the more simple heat engines are not obvious.

The total impact of direct conversion remains to be determined by future developments. It is not expected that any one direct conversion process will be a panacea for all power problems. Each will find applications based on its peculiar virtues. The first uses will be in applications where silence is more important than efficiency and in remote locations where freedom from maintenance is the determining factor. These applications will be followed by small power sources for various purposes, increasing in size and scope of applications as efficiency increases. To say how far this might go would be indulging in predictions from a clouded crystal ball. It is conceivable, for example, that there will be a period in our future

(CLOSED THERMAL CYCLE)

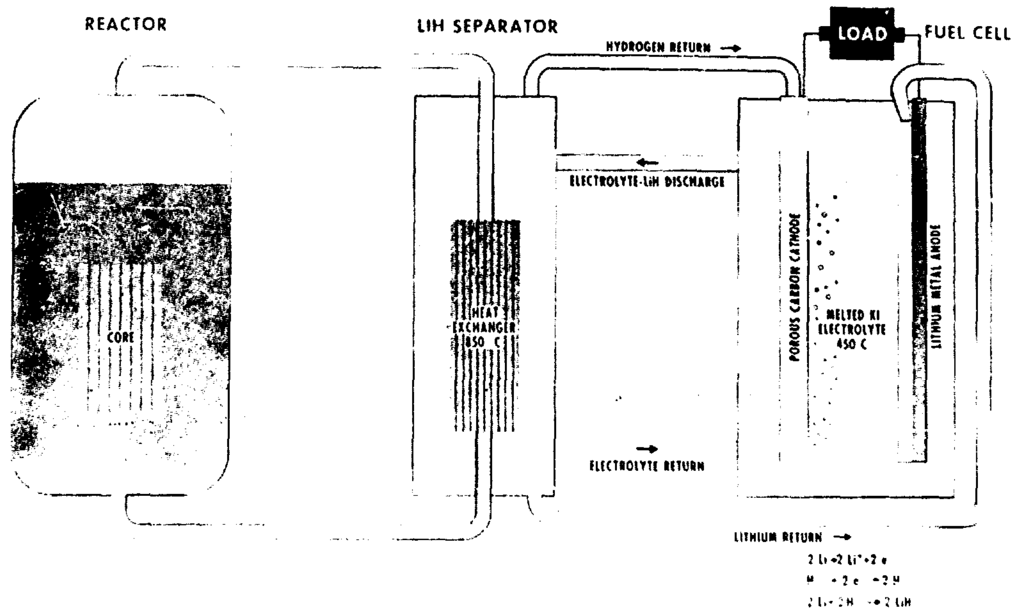

Fig. 9 - Hydride fuel cell

when central power stations will give way to individual fuel cells in every home. At a later period, when fossil fuels have become so scarce that we can no longer afford to use them for fuels, we may revert again to a more central distribution, possibly to a nuclear thermoelectric plant in each small neighborhood or country village. Or, possibly, direct conversion units will be used as topping units or waste heat scrubbers to improve the efficiency of very large nuclear turbine systems. An energy-conversion efficiency "spectrum" showing present-day and future energy conversion systems is shown in Fig. 10.

Direct conversion could thus play a dominant role in the total energy picture and the research and development program deserves a substantial effort. Whether all of the goals can be achieved depends on future developments, particularly in materials. It seems reasonably certain that with sufficient effort, direct conversion processes will solve important military problems. This is virtually assured, and it seems reasonable to expect that the progress made in connection with these developments and applications will lead to increasing civilian uses.

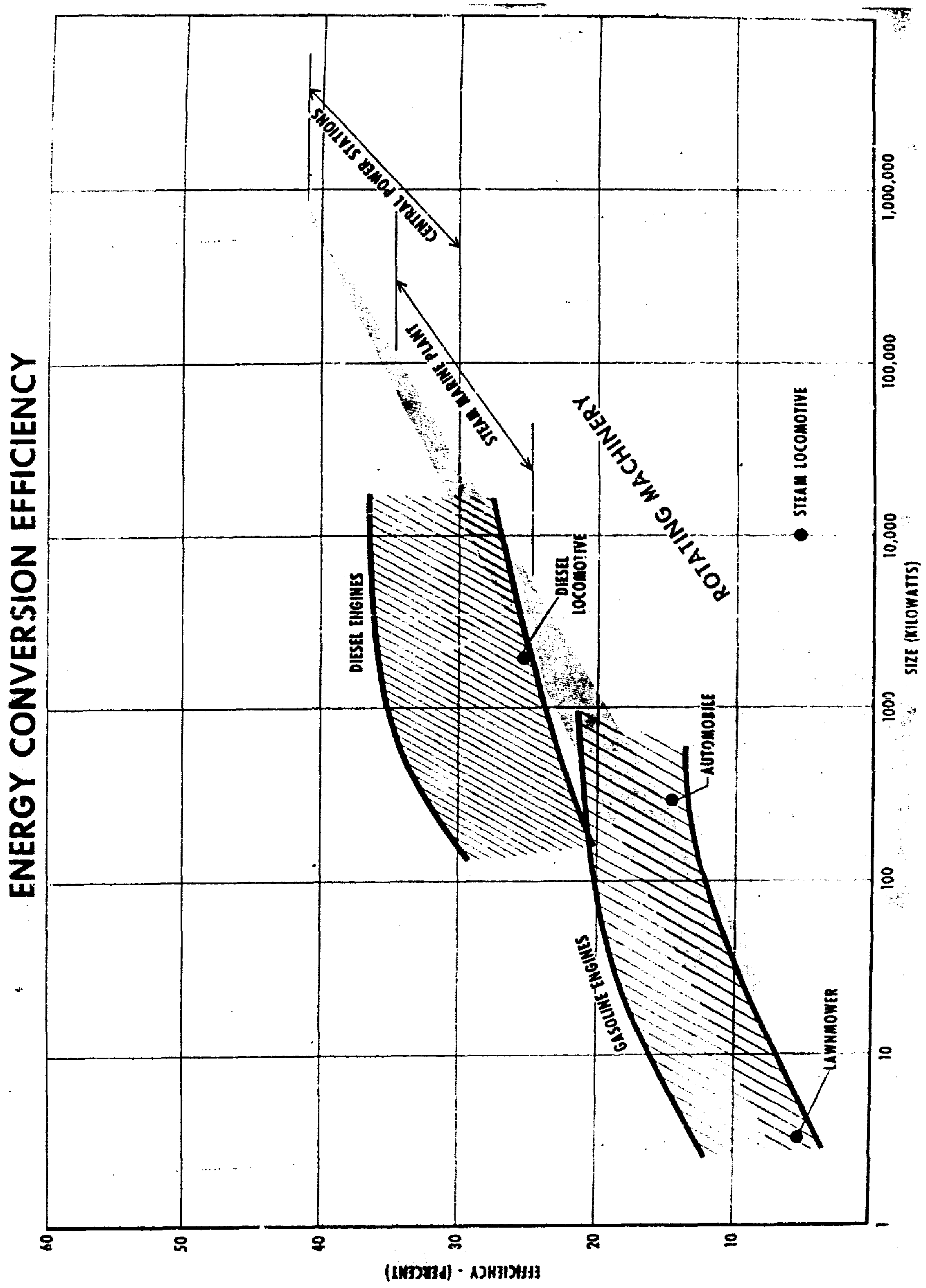

Fig. 10 - Energy-conversion efficiency

NAVY RESEARCH IN MATERIALS

Rear Admiral Rawson Bennett, USN

Chief of Naval Research

I am delighted to participate in this symposium which has brought together the most capable group of metallurgical scientists and engineers in the nation, if not the world. We in the Navy who are deeply involved in materials research and development are glad that there is an informed group in this field such as yours with whom we can discuss our problems.

Our purpose today is to give you some samples of what the Navy is trying to accomplish with our various programs in the area of metallurgy, and materials in general. It is hoped that when you have fully digested this, you may be able to come up with some novel or more efficient approaches that will expedite the progress we must make.

Simply stated, a new Navy requires new materials. Naval operations now encompass every environment between the poles of the earth and from the depths of the ocean to the heights above. Today the Navy is penetrating further into the frigid wastes of the Arctic and Antarctic, plunging deeper beneath the sea, and striding toward the outer reaches of space. We are pushing across these new frontiers because successful naval warfare depends on exploring all these environments and controlling them in the interest of national security.

It is easy to understand, therefore, why the Navy has unprecedented requirements for new materials. We are demanding materials that will withstand temperatures in the thousands of degrees and resist corrosion. In addition, these materials must combine great strength with extreme lightness.

The magnitude of the new demands on materials has led to the realization that small improvements in our present commercial alloys are not sufficient. Entirely new classes of materials must be made available, and radically new concepts in their design and engineering application must be developed. This requires extensive programs in basic and applied research as well as development.

The Navy has played a major role in furthering the support of research since the establishment of the Office of Naval Research in 1946. The Navy's broad research program in metals and ceramics and related materials will be brought out by the next speaker, Mr. Julius Harwood, head of ONR's metallurgy branch. Research in materials is carried out not only by ONR but also by the Bureau of Ships in seeking to improve submarine and surface hull design, electronics gear, and a variety of shipboard equipment, and by the Bureau of Naval Weapons concerned with developing advanced missiles and aircraft along with associated equipment. In addition, the Naval Research Laboratory, a field activity of ONR, together with several other Navy laboratories under the cognizance of the Bureau of Ships and the Bureau of Naval Weapons have their own supporting R&D programs.

Some of the Navy's programs involving these various areas are being presented today. This morning you heard Capt. Owens discuss the need for deep-diving submarines and the technical problems encountered in the design and construction of the hulls. The Navy is already exploring ocean depths far greater than man has ever penetrated before by means of the unique, deep-diving bathyscaph, Trieste. Designed and developed by Auguste and Jacques Piccard, the bathyscaph consists of a hugh tank of buoyant gasoline which can be lowered to any depth by letting in sea water and equalizing pressure. Beneath this hangs a steel sphere which can carry two observers and their instruments. Military and civilian personnel, working from NEL, under the sponsorship of the Office of Naval Research, have taken the bathyscaph down in a series of dives in the Marianas Trench off Guam. On January 23, they reached the bottom of the trench, or a depth of about 37,800 feet. Before this series of dives began, man had not gone deeper than 13,400 feet. The bathyscaph, of course, is only a research vessel. Whether or not we can ever expect to have full-scale submarines operating at such depths depends very much on materials research.

At the other end of the scale, the Navy needs new materials for more advanced aircraft and missiles, where the chief problem is one of extremely high temperature. Mr. Pellini has already spoken to you on this subject. I would like to stress the point that skin temperatures of re-entry nose-cone bodies are above the melting points of most, if not all, structural materials. Skin temperatures of advanced hypersonic craft are beginning to approach similar orders of magnitude. As a result, we are now engaged in a tremendous effort to break through the "thermal barrier."

Materials research is also the key to more efficient processes of energy conversion. This was discussed by Mr. Egli who spoke of our interest in the more effective use of solar, chemical, and nuclear energy. I might mention that the first dramatic use of solar power was the solar battery that powered a radio transmitter in the first Navy Vanguard satellite. This radio transmitter is still sending us valuable scientific data from outer space after nearly two years of continuous operation.

In the design of nuclear reactors we require core materials that can withstand not only the high temperature but also the intensive radiation of the fission process. At the same time, the material must not be inclined to absorb neutrons since this tends to stop the necessary chain reaction. Another reason for the need for high-temperature materials in this application is that the higher the temperatures at which nuclear reactors can operate, the greater the efficiency of power conversion. Compactness, small size, lightweight, serviceability, and maintenance are other parameters of special interest to the Navy in reactor design.

You have heard this morning something of our interest in the promise of thermoelectricity. Later today you will hear details of our search for suitable materials with which to exploit this process. We believe that thermoelectric power would give us units with an efficiency almost competitive with present power plants. Moreover, they would be small and without moving parts, thereby needing little maintenance and effecting substantial noise reduction.

Through thermoelectric generators and convertors, we can foresee the conversion of heat energy of the nuclear reactors used in ship propulsion directly into electricity without turbines, reduction gears, and auxiliaries. Satellites could be powered by such a thermal battery, using radioactive fuel or even solar radiation as the source of heat. All this can be forthcoming if the right materials can be found.

Refractory metals still offer great hope for high-temperature purposes, particularly now that we are making significant progress in the development of protective coatings for these metals. One new Navy-developed coating shows promise of preventing oxidation of alloys of columbium and is capable of automatically "healing" itself when flaws or defects occur. The coating, which utilizes ordinary grades of zinc as the starting material, makes it possible for the metal columbium to be utilized at temperatures as high as 2200^{0} F. Our work in refractory metals is one of the subjects which will be described in more detail today.

Another subject to be covered today is semiconductor materials. Here it should be noted that the development of the semiconductor is a direct result of basic research in solid-state physics, which has always been strongly supported by the Navy. Semiconductors are playing a prominent role in the development of infrared equipment used for the detection and tracking of airborne and missile targets. As a result, infrared is showing tremendous potential for the eventual solution of many military detection problems.

Other more specialized Navy programs will also be brought to your attention today. One of these is the brittle-fracture research being conducted at the Naval Research Laboratory where we are trying to gain a better understanding of fracture test methods and the relationship between them. You will also hear about a program at NRL concerned with the study of radiation effects on magnetic materials.

It would have been, of course, impossible to present to you in one day a complete picture of the Navy's metallurgical problems and programs. Instead, we have tried to select areas that illustrate the variety and broad nature of our research and development in this field. Lack of time has forced us to omit discussion of a number of other interesting programs, for example, composite materials, titanium, corrosion and its prevention, and our work in nonferrous alloys such as vanadium and beryllium. Nevertheless, we are extremely appreciative that we have been given this opportunity to make you better acquainted with our work.

We in naval research have learned that the American scientist and engineer likes to be faced with a stiff challenge to his ingenuity and imagination. We want you to know that we welcome your criticism and that we would like to be told when you think we have gone off in the wrong direction. You are also in a position to collect and transmit to us the latest ideas in your various specialties and to relay to us new information that may not have reached us.

This symposium is the first step in effecting a closer relationship between the Navy and the AIME. We hope this will be followed up by direct contact from those of you interested in learning more details about the field in which you are particularly concerned. Only by a constant exchange of information at all levels can we make full use of each other's capabilities and facilities.

And now I am certain that this afternoon's presentations will be as stimulating and enlightening as this morning's have been. Thank you.

THE NAVY RESEARCH AND DEVELOPMENT PROGRAM IN METALLURGY

J. J. Harwood

Office of Naval Research

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ABSTRACT

An overall summary of the Navy R&D Program in metals, alloys, ceramics, and related materials is presented. Discussion is based upon the functional utilization of materials and the objectives of materials programs rather than upon individual types of materials. Accordingly, the Navy R&D Programs in the following categories are reviewed: structural materials; materials for intermediate and high temperatures; super-high-temperature materials; materials for nuclear propulsion systems; materials for corrosion and environmental resistance; fabrication and processing; materials for energy conversion, transmission, and storage; and basic research. Areas of emphasis (refractory metals, thermal protection systems, high-strength steels, energy-conversion materials, basic research, etc.) will be noted, as well as areas of de-emphasis relative to the preceding years. The emphasis in future plans and programs will also be discussed.

* * * * *

INTRODUCTION

The objective of this paper is to present an overall summary of the Navy's research and development program which is concerned with metals and alloys, ceramics and related materials. Several phases of the program and specific research topics being studied in Naval laboratories will be discussed in detail in the five presentations to follow. The breadth and scope of the Navy program dealing with all facets of metallurgy and materials science and with most, if not all, categories of structural, electronics, and special purpose materials makes it appropriate to review the program in terms of functional groupings of materials and of the objectives of the research effort. This approach offers the advantages of enabling a program analysis in terms of aims and objectives, of providing a mechanism for interrelating the numerous individual research activities and specific program components, and of establishing a basis for pinpointing current and future areas of emphasis and priority.

It should be remembered that the program under discussion, in reality, cannot be considered as a separate entity. It is a component (and we believe a vital one) of the overall materials research and development program of the Department of Defense and, in a broader sense, of the national effort in this field. The planning and conduct of Navy programs are not done in vacuo. There is a conscious realization of work performed elsewhere and a deliberate effort to cooperate and coordinate with other agencies of the Department of Defense and of the Government at large, and as much as possible with industrially and privately supported research. Thus, program gaps or de-emphasis may exist, not only for technical reasons but also because of the recognition of research performed elsewhere.

The prime objective of the Navy R&D Metallurgy program is to make available materials with those properties required for the successful performance of naval weapons and systems and the related vehicles, equipment, components, hardware, etc. As you learned this morning, naval operations take place below, on, and above the surface of the sea. Our programs therefore are concerned with the problems of two-dimensional space, down as well as up.

We attempt to meet our objective of providing satisfactory materials with a three-phased attack. At the base is a program of basic research in metallurgy and ceramics science (or more broadly the science of materials) which aims at increasing our understanding of the relationships between microstructure and properties. By means of such research we hope to establish a solid background of information which will enable a more rational approach to alloy development and a more confident prediction and better understanding of the behavior of materials under service conditions. Closely related to the basic research effort is an applied research program in which there is an immediate concern about improving available alloys or developing new alloy systems, and related processing operations, to meet specific target properties. These studies may be related to specific end items or, as is more often the case, to a broader range of operational requirements. The third phase consists of a development, test, and evaluation program which covers the selection, design, and prototype testing of materials and components (materials engineering).

These three efforts, and particularly the first two, are not sharply separable, and indeed one of the virtues of the coordinated Navy program is the degree of interaction which exists between the basic and more applied research activities. One of the major problems with which we continuously grapple is the translation and communication of basic research findings for exploitation by applied programs.

The responsibility for basic research primarily rests with the Office of Naval Research but, as appropriate, certain areas of programmatic research and development work may be entertained by ONR. The applied research and development programs are conducted by the Material Bureaus of the Navy (e.g., Bureau of Naval Weapons, Bureau of Ships, Bureau of Yards and Docks, etc.), but they also have the option of engaging in exploratory research activities.

SCOPE OF PROGRAM

Table 1 categorizes the major research and development programs in metals and ceramics currently receiving attention by the Navy. Obviously, the list is not complete but, rather, is representative of the main areas of interest. Also, no attempt will be made to distinguish between the research performed in our own laboratories and that conducted under the outside contract program. These are interrelated and coordinated phases.

Table 1
Metallurgy R&D in the Navy

- Structural Materials (low temperatures to 650°F)
- Materials for Intermediate Temperature Range (650°-1500°F)
- High-Temperature Materials (1500°-2000°F)
- Super-High-Temperature Materials (>2000°F)
- Materials for Corrosion and Environmental Resistance
- Fabrication and Processing
- Materials for Energy Conversion, Transmission, and Storage
- Materials for Nuclear Propulsion Systems
- Basic Research

STRUCTURAL MATERIALS

The areas of interest in the category of structural materials are listed in Table 2. The objective of these programs is to improve the structural properties of available alloys, or the development of new and improved alloys for specialized naval applications. The operating temperature spectrum of the materials in this grouping ranges from subzero temperatures to about 650°F. Analysis of current programs indicates immediately that, in contrast to former years, only minor applied research support exists for aluminum, magnesium, copper, and other conventional nonferrous metals and alloys, except as needed for special applications. This is a direct reflection of the orientation of our research toward the support of more advanced naval systems involving more aggressive environments and higher temperature operations.

The primary effort, at present, is on the development and evaluation of higher quality, higher strength, notch-tough steels for submarine and ship construction, aerial vehicles, and rocket chambers.

Table 2
Structural Materials (<650°F)

- Higher Strength, Notch-Tough Steels for Submarine and Ship Construction – Including Hulls, Machinery, and Structural Components (thick sections)
- Higher Strength Steels for Aerial Vehicles and Rocket Chambers
- Titanium Alloys for Shipboard Structural Applications
- Nonferrous Alloys for Shipboard Use
- Nonmagnetic Materials
- Composite Materials
- Supporting Metallurgical Research

Although consideration of steels for conventional shipboard machinery and structural components (e.g., gears, shafting, etc.) continuously prevails, a main emphasis is being placed upon the use of high-strength steels for deep-diving submarine hulls. The need exists for steels (or other alloys) of yield strengths in excess of 150,000 psi capable of being produced, fabricated, and welded in thick sections. Weldability is a most important criterion and resistance to explosive loading conditions is mandatory. Studies are underway on the influence of metallurgical structure, composition, and impurities on the properties and fabricability of appropriate steels. The factors influencing the weldability characteristics and the properties of weldments of such high-strength steels, particularly in thick sections, are receiving special attention.

A related program involves the development and evaluation of higher strength steels for supersonic aerial vehicles, missiles, and rocket chambers. In contrast to the submarine program, we are concerned here with steels in thin gauges, with yield strengths exceeding 240,000 psi. Weight saving in the intended applications is a paramount necessity, with weldability and notch-sensitivity characteristics of weldments a gain of significance. Brittle behavior (premature failure) under multiaxial loading and notch conditions are major problem areas. Much of the research comprising this program is aimed at the control of chemistry, structure, and fabrication history to ensure adequate ductility at high-strength levels. The effects of surface treatments (plating, cleaning, etc.) on hydrogen embrittlement are being explored. Development and investigation of new steel compositions, high-strength welding electrodes, new fabrication methods (e.g., ausforming), and new construction methods (sandwich, stripwinding, etc.) constitute important program phases. New design concepts involving the relationships between the load-bearing capacity of high-strength steels and minimum ductility limits for satisfactory service operation are being investigated.

Titanium alloys are being considered as materials competitive to alloy steels in both ship and aerial vehicle applications, but the effort, under direct Navy support at this time, primarily consists of evaluation, engineering, and design.

Minor activity is continuing on conventional nonferrous alloy systems for a variety of shipboard applications but, again, this consists almost exclusively of evaluation and testing programs.

It may be anticipated that, in the foreseeable future, research and development emphasis will involve (a) continuing programs on high-strength steels with attention to weldability, fabricability, and new design concepts, (b) a more intensive investigation of titanium for submarine hull, hydrofoil, and related applications, particularly if the price of finished shapes decreases, (c) serious consideration of beryllium and its alloys as structural materials (depending upon the results of current government research and development programs), and (d) the introduction of composite materials and structures of a wide range of alloy systems involving fine-particle strengthening, fiber and flake metallurgy, thin-film technology, etc.

MATERIALS FOR INTERMEDIATE TEMPERATURE RANGE (650°-1500°F)

The areas of metallurgical activity falling within this category are shown in Table 3. Again, in contrast to prior years, it is worth noting that relatively little direct alloy research and development is being supported. Most of the emphasis is on fabrication, weldability, and evaluation of commercially available or previously developed experimental alloys.

The largest single effort is the Titanium-Alloy, Sheet-Rolling Program being administered by the Bureau of Naval Weapons for the entire Department of Defense. This program is so well known and nationally recognized that only the objective need be pointed out at this time: the development of manufacturing techniques for commercial production of titanium alloy sheet with increased uniformity, reliability, strength, weldability, and fabricability characteristics. With respect to the initial selection of alloys, this program is entering into its final stages of evaluation of components by aircraft and missile producers and of the generation of design data. However, a similar sequence of operations has been initiated for promising experimental alloys of

Table 3
Materials for Intermediate Temperature Range (650°-1500°F)

Titanium Alloys

(a) DOD Sheet-Rolling Program

(b) High-temperature alloy research

Beryllium Alloys

Vanadium Alloys

Steels for Pressurized Steam Systems

titanium with improved higher temperature strengths. Only a small amount of other metallurgical research on titanium alloys is currently supported by the Navy, in sharp contrast to the heavy emphasis during the 1950 to 1957 period.

There is also a considerable effort underway on beryllium, directed primarily toward its use in hypersonic and re-entry vehicles. Some physical metallurgy and alloy development activity is current, particularly with respect to the preparation of high-purity beryllium and the effect of impurities upon ductility and mechanical properties. Much of the program, however, is concerned with the engineering evaluation of available beryllium sheet and the fabricability of finished shapes.

Vanadium alloy research is receiving attention and some emphasis can be noted in the problem areas related to the use of alloy steels for high-temperature steam systems (1250°F) and of materials for pressurized water reactors. Current materials for steam tubing, valves, bolts, boiler, and super-heater components exhibit satisfactory performance at 1050°F. Problems are anticipated for long-time shipboard operation (>100,000 hours) with a 200-degree rise in operating temperature.

With respect to future activities: (a) The DOD Titanium-Alloy, Sheet-Rolling Program will be continued as well as a modest titanium alloy research program, particularly to improve high-temperature capabilities, (b) more intensive investigation of higher strength steels for operation in the 1000°-1500°F temperature range will be conducted, (c) depending upon the successful outcome of current R&D efforts on beryllium, a major expansion of beryllium alloy activity may occur, and (d) as in category (a), composite materials will be receiving increased attention.

HIGH-TEMPERATURE MATERIALS (1500°-2000°F)

Until just a few years ago, one of the major phases of the Navy high-temperature materials program was concerned with the nickel, cobalt, chromium, and mixed Ni-Co-Cr-Fe alloys – the so-called "super alloys." With the change in military emphasis from jet-engine technology to ballistic missile and re-entry vehicles, there is currently only a minor amount of work on the metallurgical aspects of these super alloys. There exists the strong opinion that only marginal improvements in the high-temperature capabilities of these alloys can be expected and, consequently, except for some chromium-base alloy studies, little alloy work is underway in this area. However, as part of a more general program for the investigation of improved strengthening mechanisms, dispersion strengthening and matrix ordering of nickel-base alloy systems are being studied. An outline of the areas included in the high-temperature materials field is given in Table 4.

Table 4
High-Temperature Materials (1500°-2000°F)

Nickel-Base Alloys

(a) Fine-particle (dispersion) strengthening

Cobalt-Base Alloys

Chromium-Base Alloys

Alloys for Shipboard Gas Turbine Use

Supporting Metallurgical Research

(a) Deformation at high temperatures

(b) Strengthening mechanisms

(c) Effects of environment and atmosphere on high-temperature properties

The relatively disappointing accomplishments of 10 years of research and development activity on cermets for structural applications has resulted in little current interest on cermets (other than for special rocket-nozzle applications).

Except for the evaluation of currently available materials for shipboard gas-turbine applications, the priority attached to the solution of super-high-temperature materials problems, as discussed this morning, has served to rule out any major amount of work on conventional super alloys within the immediate future. This change in emphasis represents one of the most dramatic changes of the Navy R&D Metallurgy Program to occur within a relatively brief space of time. It reflects an unusual responsiveness and flexibility of program planning to the rapidly advancing military technology.

SUPER-HIGH-TEMPERATURE MATERIALS (>2000°F)

The aggressive operating environments and extreme high temperatures associated with ballistic missiles, re-entry vehicles, hypersonic craft, rockets, new fuels, and advanced propulsion systems have presented a fantastically complex set of materials problems which require urgent solutions. The temperature spectrum for such materials ranges from about 2000°F to over 5000°F. The current Navy R&D Program in this area, as shown in Table 5, is based upon refractory metals and alloys, ceramics, graphite, and materials for thermal protection systems.

The Navy refractory alloy program is presented in detail in the paper which follows this presentation. I would only note now that this is most comprehensive in scope ranging from the preparations of high-purity materials, methods of consolidation, and alloy development (Mo, W, Ta, Cb, Re, Cr, Pt metals) to physical metallurgy research including single crystal, flow and fracture and strengthening mechanism investigations, fabrication and sheet-rolling programs, coating and oxidation protection, evaluation, design, engineering, and component testing.

The high-melting points and thermal stability of oxides and other ceramic materials have focussed attention upon the potential use of ceramics as super-high-temperature structural materials and insulating materials.

Table 5
Super-High-Temperature Materials (>2000°F)

Refractory Metals and Alloys

(a) Preparations of high-purity materials
(b) Alloy development
(c) Fine-particle strengthening
(d) Fabrication and processing
(e) Refractory alloy sheet program
(f) Coatings and oxidation resistance
(g) Compilation of engineering and design data
(h) Supporting metallurgical research

Ceramics for Missile Structure

(a) Coatings
(b) Ceramic fiber technology
(c) Fabricability
(d) Deformation and fracture behavior

Graphite

(a) Development of improved missile-grade graphite

Materials for Thermal Protection Systems

(a) Composite materials

Evaluation of Materials and Components for Rockets and Missiles

Supporting Research

(a) Generation of high-temperature thermophysical data

Because of the potential widespread applicability of ceramics (oxides, nitrides, silicides, borides, etc.) in radome and guidance applications, rocket nozzles and related propulsion components, and for structural members, much attention is being paid to processing and fabricating techniques. In addition to conventional slip casting, investigations are being made on extrusion, rolling, hydrostatic pressing, etc. These studies are supported by a strong research program on deformation and fracture characteristic of single crystal and polycrystalline ceramic materials and in physical ceramics. Various coating and deposition techniques and materials also are being investigated for thermal insulation and surface protection, e.g., arc spray coatings, plasmajets, thermitic ceramics, etc. The preparation, processing, and properties of ceramic fibers (glass, silica, oxide fibers) are also being investigated for their incorporation into composite materials.

As was emphasized this morning, graphite has become an important missile and rocket material. Surface protection techniques are being explored, as well as new production methods for the preparation of improved graphites (e.g., pyrographite) with reproducible missile-grade quality. Earlier presentations also pointed out the importance of thermal protection systems involving such heat alleviation schemes as ablation and sublimation coatings, transpiration, film or liquid-metal cooling, heat sinks, and insulating layers to prevent the heat flux from penetrating to the primary structure. It is necessary to emphasize those properties which either delay the temperature rise or lower the temperature generated in the material by its environment. Such properties as thermal capacity, emissivity, thermal conductivity, and thermal expansion assume new importance, and a program for the generation of thermophysical data on a variety of materials is underway.

Thermal protection systems emphasize the fact that no single material has the range of complex properties associated with many high-temperature applications. Therefore, composite materials and structure are being developed. Reinforced plastics and honeycomb sandwich constructions are conventional examples; others range from pure metals containing finely dispersed oxide particles to ceramics containing metal fibers and meshes. Because of the attractive thermal properties of beryllium and beryllium oxide, various combinations of BeO with refractory metal fibers and BeO with oxides and carbides are being intensively investigated, as well as the whole family of beryllides. Glass-fiber reinforced metals and refractory-metal-fiber reinforced metals show considerable promise. The new field of "fiber metallurgy" is receiving considerable attention.

Closely related is the work on fine-particle strengthening. The sintered aluminum powder concept is being extended to a variety of high-melting-point metals with striking results. There appears to be hope for developing new types of simple alloys capable of exhibiting thermal and mechanical stability at temperatures approaching their melting points. Also in the picture are simple or complex multilayer composite construction materials. Attempts are being made to take advantage of the extremely high strengths of metal and oxide whiskers and of metal films.

Future emphasis will continue to exist on refractory alloys, thermal protection systems, and composite materials. Improved ceramic materials exhibiting superior insulation characteristics will receive greater attention, and the field of intermetallic compounds for structural and related applications most likely will involve a substantial program effort.

MATERIALS FOR CORROSION AND ENVIRONMENTAL RESISTANCE

By virtue of its major operating environment, i.e., the sea, corrosion historically has been a field of major importance to the Navy. More advanced type of operations and weapons systems have superimposed upon marine corrosion a host of surface damage phenomena. Indeed, surface protection, in a general sense, is the key to many of our materials problems, particularly at high temperatures. The range of research and development activity in this field supported by the Navy is partially represented in Table 6. Our investigations range from fundamental electrochemical and adsorption research to the evaluation of proprietary protection systems, with the prime objective of developing improved means of retarding deterioration of materials and equipment. Particular emphasis is currently being placed on the investigation of the nature and protection of important corrosion reactions, such as cavitation damage, stress-corrosion cracking, liquid-metal attack, high-temperature water and pressurized steam attack, etc. A major program is underway on the cathodic protection of the active fleet, involving anode and shielding studies, current distribution analyses, and the development of practical cathodic protections systems containing energized or "sacrificial" anodes. A variety of metal and ceramic coating systems are being investigated, as well as the development and evaluation of anticorrosion, antifouling paint systems. Marine fouling, borer attack, and marine deterioration also receive attention. There is a strong supporting research program on the kinetics and mechanisms of corrosion reactions, with particular interest on the relationships between metallurgical and defect structure and surface reactivity.

FABRICATION AND PROCESSING

The introduction of higher strength and less conventional types of materials, exhibiting lower ductility properties than is the custom, of necessity require appropriate attention to the

Table 6
Materials for Corrosion and Environmental Resistance

Test Facilities for Simulated Service Testing for Marine Corrosion and Deterioration

Cathodic Protection of Active Fleet

(a) Anode studies

(b) Current distribution analysis

Studies on Nature and Prevention of Specific Corrosion Phenomena

(a) Stress-corrosion cracking

(b) Cavitation damage

(c) High-temperature water and steam corrosion

(d) Residual fuel ash attack

High-Temperature Oxidation

Development and Evaluation of Anticorrosion, Antifouling Paint Systems

Evaluation of Inhibitors, Passivators, and Surface Treatments

Metal and Ceramic Coatings for Corrosion Resistance

Supporting Research

(a) Relationships between metallurgical structure and surface reactivity

(b) Mechanisms and kinetics of corrosion reactions

(c) Surface physics and surface chemistry

fabrication and processing problems. Of the areas listed in Table 7, weldability is of special importance, as noted several times in previous discussions. The welding program is aimed at evolving fundamental information and developing and evaluating new techniques and procedures for the fabrication of high-strength, high-temperature, corrosion-resistant materials. A major effort is directed toward the evaluation of factors which determine the performance of weldments for hull structures, particularly under conditions of explosion loading. Effects of composition, mechanical properties and plate thickness on weldability, and notch toughness are being explored in consideration of hull construction for deep-diving submarines and thick steels for pressurized water-reactor construction. New or special welding techniques in general are being investigated, such as automatic welding procedures, ultrasonic welding, plasmatron and electron beam welding, "electro slag" machine-type welding, etc. The development of improved electrodes for welding high-strength steels also is underway.

Brazing and joining also are receiving special attention, particularly for the application of high-strength titanium alloys and steels. A variety of bonding systems are under investigation including adhesive bonding, exothermic ceramic brazing, metal polymer combinations, etc.

Table 7
Fabrication and Processing

Welding

Development and evaluation of optimum welding techniques for fabrication of high-strength, high-temperature, and corrosion-resistant materials

Brazing and Joining

Foundry Practice

Development and evaluation of high-strength, high-quality, shock-resistant castings

Primary Fabrication and Forming

(a) Explosive forming

(b) In-fab

Nondestructive Testing

Castings historically have been employed by the Navy for ordnance and shipboard applications, and programs for evolving new techniques and procedures for the solution of casting problems have had long standing. The major effort currently is on the development and evaluation of high-strength, shock-resistant, reliable castings for naval applications for ship hull and machinery application, for nonmagnetic (minesweeper), corrosion-resistant, and wear applications. Shell molding, precision molding, and vacuum degassing are receiving special attention. Because of the ever-present potential of castings for critical naval application in advanced weapons systems, preliminary consideration is being given to the establishment of a coordinated and integrated research and development program leading to the ultimate production of high-quality castings.

The increasing application of high-melting-point alloys, and their attendant processing difficulties, has directed attention to the investigation of new forming and fabrication procedures, such as explosive forming, controlled atmosphere facilities for hot-working refractory metals (In-Fab), ausforming, etc.

Investigation of improvements in nondestructive testing methods remains a constant program component.

MATERIALS FOR ENERGY CONVERSION, TRANSMISSION, AND STORAGE

The problems of guidance and detection of military vehicles and the need for new types of power and energy-conversion systems, as pointed out in an earlier paper, have focussed a major share of our research attention upon the (electronic) transport properties and behavior of solids and upon solid-state devices. Certainly this area, as outlined in Table 8, has achieved stature equal to the problems of developing improved structural materials.

Table 8
Materials for Energy Conversion, Transmission, and Storage

Thermoelectric Power (TEP) Materials

(a) Measurement of TEP parameters and efficiencies
(b) Materials research and development
(c) Device studies
(d) Supporting metallurgical and solid-state physics research (transport phenomena)

Magnetic Materials

(a) Al-Fe-Si system
(b) Ferrites
(c) Garnets
(d) Rare earth alloys
(e) Irradiation effects
(f) Supporting research on molecular magnetism

Semiconductor Materials

(a) Infrared systems

Transducer Materials

Energy-conversion systems, and particularly thermoelectric power materials, comprise one of our major programs. A detailed discussion of TEP materials is contained in one of the papers to follow. It is of interest to note here, however, that this represents a field requiring the common attention of metallurgists, solid-state physicists, and chemists, in view of the types of semiconducting materials being investigated, i.e., intermetallics, mixed valency oxides, doped carbons, sulfides, nitrides, and even organic compounds.

Magnetism and magnetic materials also have a long-standing research history in the Navy. There is a substantial program on the development of new materials and processing methods to improve existing materials for magnetic components used in ordnance, navigational, control, and communication systems. The development of magnetohydrodynamic propulsion systems requires magnetic materials with an order of magnitude improvement over existing materials.

Iron-aluminum alloys have been intensively investigated. Thermenol and Alfenol, developed by the Naval Ordnance Laboratory, are by now well-known materials. Current attention is on rare earth alloys, ferrites and garnets, and on preparation and processing methods. The effects of irradiation on the properties of magnetic materials (the subject of a later paper) is being fully explored. The materials program is supported by a strong research program on molecular magnetism, i.e., magnetic structure and properties of solids with emphasis on the interatomic and molecular forces involved.

Semiconductor research in the Navy has had heavy emphasis on the optical properties and photo effects for infrared systems. As will be more fully detailed later, the properties of intermetallic semiconducting compounds (sulfides, tellurides, arsenides, etc.) have been investigated to obtain a better understanding of the mechanisms responsible for the photo effects and the discovery of new effects. The relation between purity (or deliberate impurity doping), defect structure, and photoconductivity has received special attention.

MATERIALS FOR NUCLEAR PROPULSION SYSTEMS

The Navy program on pressurized water nuclear reactors for submarine and ship propulsion is sufficiently well documented such that it is not necessary to review. Many metallurgical and corrosion problems required solution for the successful development of the NAUTILUS and related nuclear propulsion systems. In the field of nuclear reactors for aerial vehicles there is a small effort on the problems of liquid metals as heat-transfer media involving corrosion and mass transport studies and the evaluation of container and piping materials. Compatibility of structural materials with molten lithium and the mechanism of surface damage are being investigated. Much of the research in the high-temperature materials and corrosion programs provides support to the problems in this area.

BASIC RESEARCH

It is manifestly impossible in such a brief summary of the Navy R&D Program to adequately describe the comprehensive metallurgy and ceramics basic research program supported by the Navy through its sponsored contract research activity and its "in-house" laboratory effort. Hundreds of individual research tasks and several millions of dollars are involved annually. Fortunately, the program of the Office of Naval Research previously has been presented before the AIME at the 1955 Annual Meeting in New Orleans, whereas the applied research program has never received a similar public presentation. Moreover, the results of Navy sponsored research (much of which is carried out at universities) is continuously being reported in the scientific literature.

As stated in the introduction to this paper, basic research is considered a most essential component of the overall Navy Materials R&D. The program has a dual motivation of research by necessity and research for opportunity. That is, the basic research program not only directly supports the applied research and development phases but, in addition, provides the fountain head of new ideas, new concepts, and new materials for these more applied programs. Because of our objective in trying to improve the understanding of the relationships between structure (micro, crystallographic, atomic, and imperfection) and properties we are obviously concerned with all facets of research in physical metallurgy and physics of metals. Some of the prominent areas of research currently receiving our attention are listed in Table 9. It is important to note, again, the attention to electron transport properties and behavior in addition to the studies on flow and fracture and solid-state reactions. From a materials orientation viewpoint, the metallurgy research program has a primary emphasis on structure-sensitive properties and reactions, i.e, how does the composition, microstructure, defect concentration, impurity level, thermal-mechanical history, etc., control the various physical and mechanical phenomena which underlie the applications of alloys and ceramics. Strong support to the Materials Research programs comes from related research programs in solid-state physics and chemistry.

CONCLUSION

It is obvious that many difficult materials problems face the Navy as a result of its advancing technology and weapons systems. We are confident that the applied research and development programs now underway, or being planned, supported by a strong basic research program, will lead to major improvements and to the introduction of new types of materials required to solve our problems. This is particularly true if we maintain the responsibility and capability of being alert to exploit any scientific or engineering advance in materials and processes, no matter what its origin may be.

Table 9
Basic Research

Mechanical Behavior of Solids
(Electron) Transport Properties in Solids
Imperfections in Solids
Crystal Growth and Morphology
Nature, Properties, and Behavior of Surfaces (including corrosion)
Phase Transformations
Diffusion and Mass Transport
Structure and Properties of Liquids
Alloy Theory and Cohesion
High-Pressure Research
Whiskers and Thin Films
Optical and Thermal Properties of Solids
High-Temperature Properties and Reactions
Instrumentation and Techniques
Radiation Effects
Magnetic Properties and Magnetism
Strengthening Mechanisms in Solids

With respect to long-range planning, we retain the conviction that as we recognize the needs of the future, we should initiate the research in the present. Program planning becomes than a matter of flexibility in phasing and emphasis to take immediate advantage of our increasing knowledge about the properties and behavior of metals and ceramics and about the science of materials, in general.

THE NAVY REFRACTORY METAL PROGRAM

T. F. Kearns and J. Maltz

Bureau of Naval Weapons

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ABSTRACT

Increasing requirements for structural and power-plant materials capable of operation above 1800^{0}F have stimulated Navy interest in the refractory metals. Major emphasis has been placed upon tungsten, tantalum, molybdenum, columbium, and their alloys. The basic problems of consolidation and working to produce mill products on a commercial basis have been solved for most of these materials. Improved techniques for increasing yield and handling the more refractory compositions are under development. Alloy development is rather well advanced for molybdenum and columbium, less well advanced for tantalum, and barely begun for tungsten. The state of progress in related areas, such as fabrication, welding, and protection against oxidation, is briefly reported. The status and accomplishments of the Bureau of Naval Weapons Refractory Metal Sheet-Rolling Program are detailed.

* * * * *

The refractory metals are defined in terms of high-melting point, as listed in Table 1. The cutoff point may be 3000^0 F or any other convenient and arbitrary figure. For the purpose of the current presentation the discussion will be largely confined to the upper portion of the table. When considerations of price and scarcity are added, attention is focussed on tungsten, tantalum, molybdenum, or columbium for any but the most specialized applications. This is not to say that the Navy has no interest in the lower portion of the table but only that such interest will not be dwelt upon here.

Tungsten and molybdenum are neighbors in Group VI A of the Periodic Table where interatomic bonding is such as to emphasize strength and rigidity at the expense of low-temperature ductility. They have low solubility for interstitial elements and are prone to further embrittlement at low contamination levels. Tantalum and columbium are in the adjacent Group V A. As compared to tungsten and molybdenum they have greater solubility for interstitials. They

Table 1
Refractory Metals

	Melting Point ($^{\circ}$C)	($^{\circ}$F)	Density (g/cc)	Young's Modulus (psi x 10^6)
Tungsten	3410	6170	19.3	50
Rhenium	3180	5740	20.0	67
Tantalum	2996	5425	16.6	27
Osmium	2700	4900	22.5	80
Molybdenum	2625	4760	10.2	45
Ruthenium	2500	4535	12.2	
Iridium	2454	4450	22.5	75
Columbium	2415	4380	8.57	15
Rhodium	1966	3520	12.4	41
Chromium	1890	3430	7.19	36
Titanium	1725	3140	4.5	15
Vanadium	1715	3125	6.11	22

are somewhat weaker, considerably less stiff, and much less difficult to fabricate. Although all four metals have body centered cubic lattices, tungsten normally has a ductile-to-brittle bend transition range well above room temperature, molybdenum has one near room temperature, columbium remains ductile, if not grossly contaminated, well below room temperature, and tantalum remains ductile to 200°F or below. As a result of this difference, the four metals appear to have separate, but overlapping, areas of usefulness depending upon the relative importance of strength and fabricability in the end-item one wishes to construct.

The Navy refractory metal program was started in 1947 when it became clear that the trend toward higher and higher equipment operating temperatures had no apparent top limit other than the capabilities of available materials. It was clear that as temperatures approached and exceeded the melting points of the then used iron, nickel, and cobalt-base alloys, new materials with higher melting points would be required. The refractory metals provided one promising family of materials which met this requirement.

The Navy placed initial emphasis on the development of molybdenum alloys. This decision was based upon cost and availability advantages of molybdenum over columbium, tantalum, rhenium, and the platinum group metals and density advantages over tungsten, tantalum, and rhenium. It may be recalled that columbium supplies at that time were very much more limited than they are today. It may also be recalled that rotating parts such as turbine blades were then receiving major attention and that the stresses in such parts, resulting from centrifugal force, increase as a direct function of density.

As a result of more than a decade of steady progress there has been created a large body of technical information and capability in molybdenum alloys. A few high points are listed below:

1. Room temperature brittleness was related to grain boundary oxide formation. A carbon deoxidation technique resulted in the production of workable material.

2. The size limitations of the then-existing powder metallurgy techniques for producing large ingot were overcome by the development of the vacuum arc-casting process. Twelve-inch-diameter, arc-cast ingots weighing 1800 pounds are now regularly produced, and even larger ones will soon be available.

3. The cast ingot breakdown problem was solved - at least on an interim basis - by the application of the glass extrusion process. The term "interim basis" is used because existing breakdown equipment can operate with only a small extrusion ratio and uneconomical recovery rates. More desirable solutions are in sight and will be described later.

4. Vacuum technology for controlling interstitial contamination during processing has been developed.

5. Analytical techniques for impurities in the parts-per-million range have been improved.

6. A number of useful alloys have been developed. The No-Ti-Zr-C alloys are strengthened by a mechanism which, though not yet perfectly understood, involves a fine dispersion of carbides and perhaps oxides. In some of the more interesting new alloys, titanium has been increased from 0.5 percent to about 2 percent with proportionate increases in the amount of carbon. The use of solid-solution strengtheners to supplement the dispersion effect has produced alloys with extremely high tensile strength at 2400° and beyond.

Inasmuch as none of these alloys respond to hardening by heat treatment, they are used in the hot-cold worked condition. Consequently, a high recrystallization temperature is important. The recrystallization temperatures of the molybdenum alloys in preproduction status are above 2600° F. This is an advancement of some 700° F over that of pure molybdenum.

7. Dramatic increases in ductilities have been achieved by rather large additions of rhenium to molybdenum, as illustrated in Table 2. The effect is also noted, though not as dramatically, when rhenium is added to tungsten. Recently, research has demonstrated that several effects are involved: oxygen redistribution in the grain boundries, introduction of a twinning mechanism for deformation, and unlocking of dislocations. Although cost and availability make the use of rhenium in such percentages impracticable in alloys of general application, and no plentiful substitute has as yet been found, certain limited applications, as in weld filler metal, are likely. More important, this work has provided a spur to refractory metal research. There is now some evidence that some of the rhenium effects may be conferred by a combination of more plentiful addition elements.

Table 2
Workability of Cast Molybdenum-Rhenium Alloys

Rhenium (Atomic %)	Percent Reduction before Cracking		
	Room Temp.	500° C	1250° C
0	10		10-15
5	-	14	15
15	-	20	22
25	18	>94	32,>95
30	19	>93	>95
35	>95	>94	>94
40	18	>93	>93
50	10	10	10

About three years ago the Navy, foreseeing the need for refractory metals for major new applications, expanded and intensified its refractory metal program. Table 3 shows the program which was mapped out. Several portions of that program have already been completed. Others are in progress. As an example we may consider the item of high-purity refining. It is only by approaching the ultimate in purity that we can determine whether true ductility is obtainable at and below room temperature in such metals as tungsten or chromium (or for that matter, many other metals such as beryllium). Table 4 illustrates how far we have come by electron-beam, floating-zone techniques in the refinement of tungsten.

Table 3
Navy Department Refractory Metals Program

A. Compilation of Available Data

B. Establishment of Adequate Source of Materials

   1. Availability of material
   2. Methods of extrusion, melting, and consolidation
   3. High-purity refining

C. Alloy Development

   1. Binary and ternary phase diagrams, as necessary
   2. Solid-solution alloys
   3. Precipitation hardening systems
   4. Other high-temperature strengthening techniques

D. Physical Metallurgy

   1. Self-diffusion and interdiffusion coefficients
   2. Transformation mechanisms and kinetics
   3. Recrystallization behavior
   4. Plastic and fracture behavior
   5. Metallography and fractography

E. Corrosion, Oxidation, and Surface Protection

   1. Environment resistance
   2. Mechanism and kinetics of oxidation
   3. Surface protection

F. Evaluation of Material

   1. Workability
   2. Fabricability, including welding
   3. Design data, including mechanical and physical properties
   4. User and service evaluation

Table 4
Purification of Tungsten by Zone Melting*

Element	Analysis (ppm)	
	Starting Material	After Zone Melting
Ca	10	<1
K	40	<1
Na	20	<1
Fe	10	<1
Mo	40	1
Si	20	<1
C	70 ± 20	20 ± 10
O	3^{+5}_{-3}	<1
N	$0.3^{+1.0}_{-0.3}$	<1
H	$0.1^{+0.3}_{-0.1}$	No analysis

*Courtesy General Electric Co.

In the raw material area, vacuum technique is being used to produce extremely fine pure powders of columbium and of tantalum (less than μ diameter as a possible starting material for dispersion strengthening. Dispersion strengthening of molybdenum is also being attempted by internal oxidation of Mo-Ti and Mo-Cb alloy powders which, having the dispersed oxides already distributed throughout the powder particles, may be compacted, sintered, extruded, and forged or rolled to shape. The phenomenon of oxide dispersion strengthened molybdenum has, of course, already been reported. The objective here is to achieve the increases in recrystallization temperature and strength while maintaining good low-temperature ductility.

In alloy development, studies of the Mo-Ti-Zr-C series are being continued. Binary alloys of tungsten with a variety of other metals and ternaries of molybdenum-tungsten with various additions are also under study. A series of platinum-base binary alloys is also receiving attention. In tantalum, ternaries with about 10 percent tungsten, sometimes supplemented with Hf or Re, are the areas of concentration, although some alloys of higher tungsten content are being checked.

It may be of interest to note in passing some results achieved in vanadium and chromium alloy development programs. In vanadium, short-time tensile strengths of 50,000 psi at 2000° F for annealed materials have been attained. On a strength/weight basis this compares favorably with the best available sheet materials at this temperature. In chromium, it is of interest to note that yttrium and cerium can be added to the very limited list of additions which lower the ductile-to-brittle transition temperature. The lowest bend transition temperature, 40° F, has been attained with hydrogen-reduced chromium containing 1-percent yttrium.

In fabrication, a series of studies is in progress ranging from explosive forming and spinning of sheet and other preforms to plasmajet spraying. This work is directed mainly at tungsten and molybdenum alloys in view of the fabrication difficulties encountered with these materials.

The plasmajet and the electron beam are being employed as possible improved tools for welding. The theory of ultrasonic welding is being refined. Figure 1 is a photomicrograph of a cross section of a molybdenum alloy weld made ultrasonically. The faying surface has virtually disappeared even though no melting or gross recrystallization can be observed in the weld area.

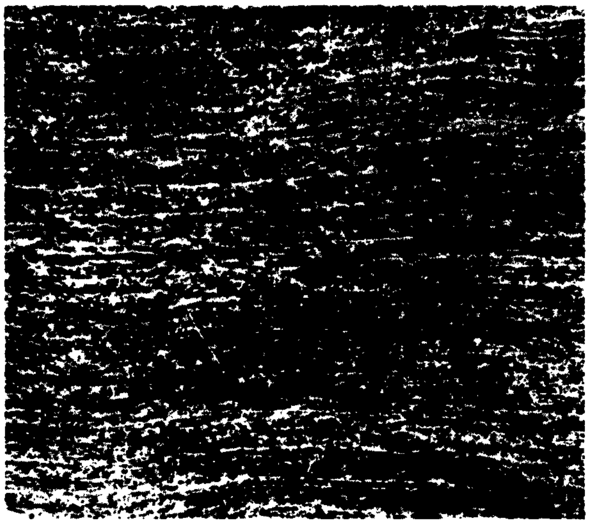

Fig. 1 - Photograph of a cross section of an ultrasonic molybdenum-alloy weld

In the protective coating field there is still much to be desired. Much of the past work on protective coatings for molybdenum, starting with the silicide coating formed in place by hydrogen reduction of SiCl, has been previously described by others. The silicide coating protected molybdenum against oxidation very successfully for several thousand hours at 2000° F. Its shortcoming was its inability to tolerate any distortion of the basic metal, coupled with sensitivity to damage. Electroplated coatings, dipped coatings, sprayed coatings, cementation coatings, and even refractories trowled on 1/4 inch thick have all been tried and have all achieved success within their limitations. However, as in the case of long-time operation at temperatures over 3000° F, or where high thermal shock or abrasive damage is encountered at lower temperatures, there is still room for improvement.

In its current work the Navy is evaluating several of the more promising molybdenum-alloy coatings under conditions of stress, temperature, damage, thermal shock, and oxidation environment characteristic of end-item exposure. It is also studying possible new coating materials, primarily metal-ceramic composites.

In this field one new development seems rather remarkable. Figure 2 is a photomicrograph of a coating produced by diffusing zinc into the surface of columbium. It doesn't seem to make much difference how the zinc is applied – whether by dipping, spraying, vapor deposition, or electroplating. After diffusion, there are formed compounds which vary from $CbZn_3$ on the

Fig. 2 - Photomicrograph of zinc coating diffused into columbium surface

outside layers beneath the surface oxides, through the very hard lower zinc compounds to the basic columbium. This coating has protected columbium against not only surface oxidation but also against oxygen pickup as evidenced by no change in the hardness in 500 to 800 hours at 1800° F. The coating seems to have excellent throwing power, coating without difficulty, for example, the inside of long thin-drilled holes. Perhaps its outstanding characteristic is the ability to withstand damage. Figure 3 is a zinc-coated columbium specimen across which a 3/8-inch-wide slot was deliberately milled well below the coating thickness. The specimen was subsequently heated in air for 20 hours at 1800° F, a time long enough to convert an unprotected specimen completely to oxide. The zinc oxide was then broken away intentionally to expose the metal. The zinc coating was able to repair even so gross a damaged area.

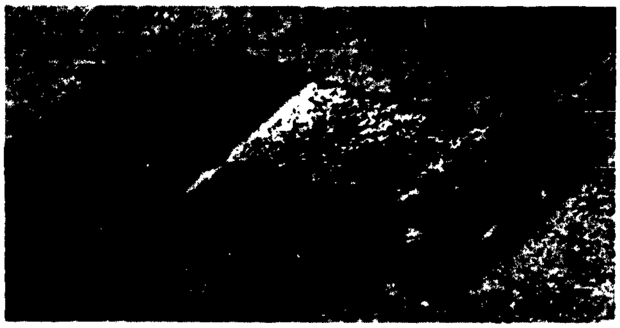

Fig. 3 - Heat-treated (20 hours at 1800° F), zinc-coated columbium specimen with 3/8-inch-wide slot milled in the surface below the zinc-coating thickness

This investigation is still in the very early state but will be reported as soon as practicable in the technical literature. The zinc coating has been tried on the other refractory metals, with some success on tantalum but little success on molybdenum and tungsten. It is limited, in its present form, to temperatures on the order of 2000° to 2200° F.

The program just outlined is quite broad and is aimed at studying many phases of refractory metal science. However one portion of it, in particular, seemed to require greater emphasis. It had been estimated that the bulk of the newer requirements for refractory metals would be for material in sheet form and that the rate of growth of the need was too great to be met by normal commercial development. Accordingly, a major effort in refractory metals development now in progress is aimed at the production of uniform high-quality sheets. This "Refractory Metal Sheet Program" is quite analogous to the earlier Titanium Sheet-Rolling Program. The objective of the sheet program, briefly, is to put the laboratory advances that have already been achieved to work in the form of a fully reliable product whose properties are known and can be depended upon for design purposes.

In order to develop the kind of information that is needed for control of the production processes it is necessary to produce a good quantity of material. The program is therefore a large one, costing several million dollars. Under it, thousands of pounds of refractory metal sheet will be produced. It is a cradle-to-the-grave affair, starting with the processes for production of the raw material and proceeding through consolidation, melting, ingot production breakdown, rolling to sheet, measurement of the sheet properties and, finally, evaluation of the manufacturing characteristics and actual performance of the material by construction and testing of a few typical end-items, such as a ramjet motors or rocket nozzle inserts.

The sheet program itself does not include any significant effort in alloy development. In fact, one of the ground rules for inclusion of alloys in this program is that the laboratory work shall have already been done and that the alloy shall have been produced in quantities large enough to remove any uncertainty regarding the properties of the alloy. This quantity is on the order of 5-inch to 6-inch-diameter billets from which sheet 12 inch to 18 inch wide by 3 feet to 4 feet long have been made. This ground rule will probably be waived in the case of tungsten and some effort may also be applied to other alloys at earlier stages but, in general, alloys furthest along in their development lines will be emphasized.

In a program of this size, the penalty for error is large indeed. In order to minimize this possibility, as well as to insure proper consideration of all factors such as possible production difficulties, the actual perforance requirements imposed in end-items, the kind of manufacturing operations that will be encountered, and the importance of characteristics such as weldability, etc., the Navy, through the Materials Advisory Board of the National Academy of Sciences, has enlisted the services of an advisory panel to help keep this program most effectively oriented. The panel is composed of people representing the materials producers, designers, and end-item manufacturers.

One of the first efforts under this program has been to examine, on the one hand, all available data on refractory sheet alloys and, on the other hand, all foreseeable military requirements for such alloys and to formulate a set of realistic target properties which sheet produced under the program should strive to meet. Candidate alloys are now being examined carefully and those most likely to meet the goals will be selected for inclusion in the sheet program.

Table 5 is a partial list of candidate alloys. There are, of course, many more alloys being screened but most of the others do not yet meet preproduction criteria for candidate alloys. Figure 4 shows the strength-to-density ratio of some of the strongest candidates in the range 2000° to 3000° F. More recent data, not shown, are available for considerably higher temperatures. On a strength/weight basis the competition between molybdenum and columbium alloys is close around 2000° F. At higher temperatures we have in the molybdenum-alloy series the highest strength/weight alloys now available. Approaching 3000° F it seems certain that tungsten or tantalum-tungsten will be unrivalled in this respect.

Table 5
Candidate Refractory Sheet Alloys

Molybdenum	Columbium	Tantalum	Tungsten
0.5 Ti	15 W - 5 Mo - 1 Zr	7.5 W (PM)	No Alloys
0.5 Ti - 0.07 Zr	15 W - 5 Mo - 5 Ti - 1 Zr	10 W (PM)	
0.05 Zr	1 Zr	10 W (EBM)	
0.5 Zr	10 Ti - 10 Mo	PM: powder metallurgy EBM: electron-beam melted All others: arc melted	
1.25 Ti - 0.15 Zr - 0.15 C	33 Ta - 0.7 Zr		

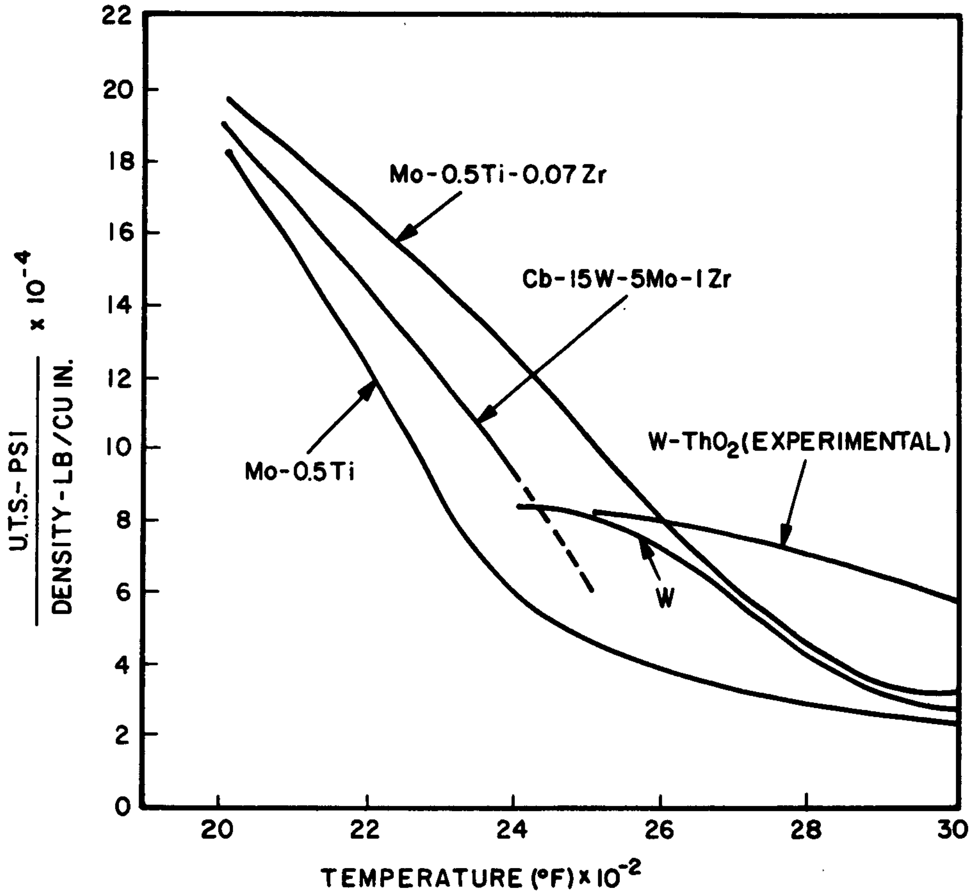

Fig. 4 - Strength-to-density ratio for some of the best molybdenum and columbium alloys in the temperature range 2000° to 3000° F

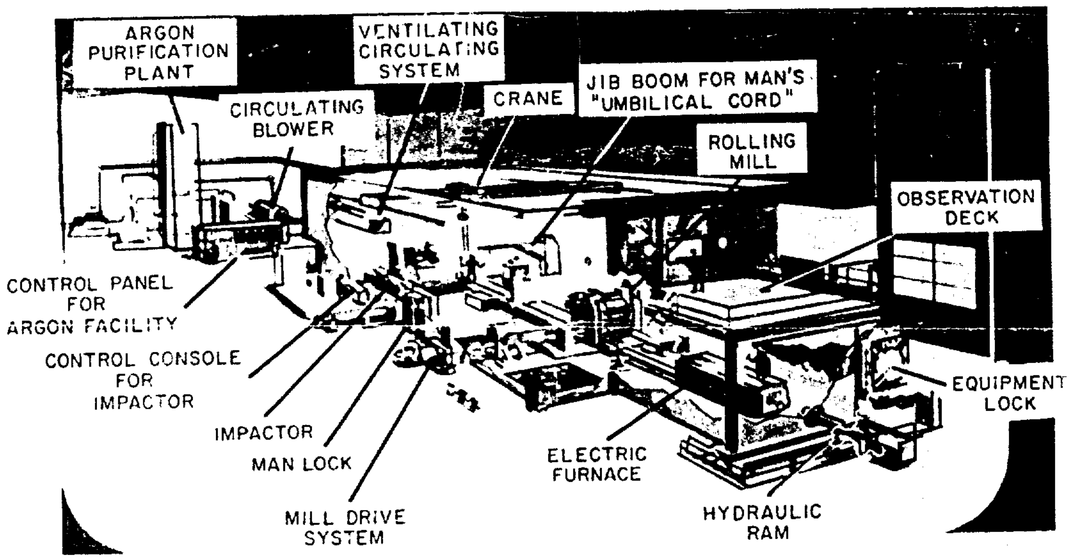

Fig. 5 - Air-tight facility for processing refractory metals under true hot-working conditions

Several studies are already in progress under the sheet-rolling program. The first is the production of higher quality molybdenum alloy sheet approximately 36 x 96 inches by the best-available production techniques involving arc-melted ingot. Mo-0.5%Ti and Mo-0.5%Ti-0.10%Zr have been selected for inclusion in this program.

A second project involves the production of moylbdenum alloy sheet by powder-metallurgy techniques. Although powder metallurgy has some real advantages over arc melting – fine grain size for example – no alloys based upon powder metallurgy have yet been developed which are competitive with the best arc-melted alloys in the higher temperature range. This is attributable to current alloying capabilities of the powder-metallurgy technique.

In another study, unusual techniques are being examined to produce the finest practicable grade of molybdenum for subsequent consolidation. In particular, the effects of various interstitials on sheet quality are being tied down. Some of the techniques being tried are bomb reduction (to control hydrogen), hydrogen reduction and post-reduction processing (to control oxygen), and electron-beam melting (to control carbon).

The practicability of direct extrusion of powder to sheet bar and of direct rolling of powder to sheet, as a means of eliminating the costs and possible shortcomings of melting and ingot processing, or pressing and sintering, is also being investigated.

The most recent program covers the production of high-quality 18 x 48 x 0.060-inch tungsten sheet. In this case, because of the lack of suitable tungsten alloy candidates, the first effort will be aimed at unalloyed tungsten.

Supplementing the Bureau of Naval Weapons Refractory Metal Sheet-Rolling Program, the Air Materiel Command of the Air Force is sponsoring programs on the development of manufacturing methods for large columbium alloy sheet and extrusions.

This presentation will be concluded with a discription of the highly novel facility just being completed and placed in operation for the Bureau of Naval Weapons at Bridgeville, Pennsylvania. This is an air-tight room, approximately 80 x 40 x 25 feet for processing refractory metals under true hot-working conditions. The room shown schematically in Fig. 5 is filled with argon and equipped with a recirculation and purification system capable of maintaining the total impurity level at 50 parts per million or less. The principal pieces of equipment at present are a forging impactor and a versatile rolling mill, which, together, are capable of processing ingot to sheet at temperatures up to 4000°F. The facility was sponsored by the Navy specifically to provide this processing capability as an aid to research and development programs, which may be scheduled for use by arrangement with the Bureau of Naval Weapons.

All in all, we feel that the Navy has a broad, agressive refractory metals development program which should contribute significantly to the advancement of this important area.

SEMICONDUCTOR RESEARCH IN THE NAVY

Wayne W. Scanlon

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ABSTRACT

Semiconductor research in the Navy is oriented toward knowledge of the optical properties of these materials for application in the detection and observation of objects, or communication with and guiding military devices. Investigations are conducted at three Navy Laboratories: NOL, White Oak; NOL, Corona; and NRL, Washington. The investigations consist of the study of the basic physics and chemistry of semiconductor materials used for infrared detectors, windows, etc., and for photoconductive purposes. The effects of impurities and crystal imperfections on electrical properties, such as the Hall effect, conductivity, etc., are studied. A theory of electrical noise characteristics has been found which explains the basic characteristics of semiconductors and allows the prediction of noise behavior. Advances in materials preparation techniques have made possible more precise studies of these materials.

* * * * *

Semiconductor research in naval laboratories is motivated principally by the Navy's interest in using infrared radiation for detecting, ranging, and observation of objects, or communicating with and guiding military devices. Semiconductors possess a number of characteristics which enable them to perform remarkably well in many of these applications. Certain semiconductors are the most sensitive infrared detectors known. Others make windows and lenses which are superior to any other infrared optical material. The sharp optical absorption edge of semiconductors makes them admirably suited as filters for excluding undesirable radiation. In addition, the influence of infrared radiation on the electrical and magnetic properties of semiconductors has proven to be an extremely valuable means for investigating the basic physics of semiconductors.

The maximum utilization of semiconductors in the Navy's infrared applications is dependent upon a thorough knowledge of the basic physics and chemistry of these materials. While much is known of the electrical properties of certain elementary semiconductors, such as germanium and silicon because of their commercial application in transistors or diodes, knowledge of the optical properties of these materials has been of somewhat less interest. Furthermore, many of the semiconductors known to be the most sensitive infrared detectors, such as

PbS, PbSe, and PbTe, have been almost completely ignored by the transistor people. Research in Navy laboratories has been directed toward increasing our knowledge of the optical properties of the elementary semiconductors and both the electrical and optical properties of certain classes of compound semiconductors possessing useful infrared characteristics.

The research is being conducted principally at three locations: the Naval Research Laboratory, Washington, D. C., the Naval Ordnance Laboratory, White Oak, Md., and the Naval Ordnance Laboratory, Corona, California. The three programs are basically different, being oriented by the different interests of the groups and the available special research equipment.

The Naval Ordnance Laboratory, White Oak, is interested principally in those semiconductor materials which have small energy gaps of the order of a few tenths of a volt. These semiconductors have optical absorption edges and photoconductivity within the important range of wavelengths from approximately 1 to 10 microns. Such materials are called intrinsic photoconductors. Typical examples of small-energy-gap semiconductors are PbS, PbSe, PbTe, and InAs.

The Naval Research Laboratory is interested in larger energy gap semiconductors, such as germanium and silicon which have impurity levels within a few hundredths or a few tenths of a volt of conduction bands. These materials when cooled to liquid nitrogen or helium temperatures are photoconductive for radiation of wavelengths from approximately 10 to 150 microns. They are called impurity photoconductors.

The Naval Ordnance Laboratory, Corona, has been the central testing laboratory for infrared cells made at various places in this country and abroad. They have provided valuable comparative information on photoconductive cell performance.

Much of the research at the Navy laboratories is of a nature basic to understanding the photoconductive mechanism and the related optical properties of semiconductors. For example, the work at NRL on the far infrared absorption in germanium and silicon, beyond the main band absorption edge where impurity absorption occurs, has contributed much to the understanding of impurity energy levels in semiconductors. These investigations extended out to wavelengths of about 40 microns originally, but recently they have instrumentation increasing the limit out to about 150 microns. One of the practical results of this work is the zinc-doped germanium infrared cell which responds to radiation out to about 40 microns when cooled to 4°K. Current investigations at NRL are directed toward an understanding of the nature of band edges in semiconductors based upon infrared cyclotron resonance studies and magneto-optical absorption measurements.

At the Naval Ordnance Laboratory, White Oak, research on small-band-gap semiconductors like PbS, PbSe, and PbTe encountered a materials problem not found in similar investigations on elementary semiconductors. Many of the small-band-gap semiconductors are compounds, some of which have a substantial polar character in the interatomic bands. Crystals of such materials may exist over a small range of composition near the stoichiometric proportions through the incorporation of lattice vacancies in either sublattice or interstitial atoms. These imperfections produce donor or acceptor levels in the semiconductor in addition to those produced by impurity atoms. The concentration and kind of these imperfections is a complicated function of the temperature and composition of the gaseous and liquid phases surrounding the crystal. A materials problem involving phase relationship had to be solved before reliable investigations of the Hall effect, electrical conductivity, and similar properties could be made. NOL, White Oak, has made a number of experimental and theoretical contributions to this physical-chemical problem of the phase relations in compound semiconductors and has helped in defining the phase diagram in PbS and PbTe. The information so gained made it possible to prepare a group of crystals of PbS and PbTe having a desired range of electrical properties.

Measurements of Hall effect and electrical conductivity in these crystals clarified the problem of the energy gap in these materials and definitely established that they are intrinsic photoconductors. Other basic characteristics of the semiconductors were determined, such as the mobility of electrons and holes, scattering processes, carrier lifetimes, optical absorption properties, and effective masses.

The radiative recombination time for electrons and holes in crystals was found to be much too short to account for the observed photoconductive lifetime in films of these materials. Hence, we proposed that a trapping process is important in photoconductive films for extending the carrier lifetime. We pursued this subject further in PbS and PbSe films and established that oxygen produces the trapping levels in films. Using the techniques of field-effect studies we were able to estimate the trap depths, concentrations, and cross sections.

Hall effect and resistivity studies on crystals and films clarified the problem of the photoconductive mechanism. It was basically a change in the carrier density induced by photon absorption, rather than that plus a barrier modulation effect induced by the radiation, which is responsible for the photoconductivity in the lead salts.

Further information on these materials was obtained from the electrical noise characteristics. We were curious about noise for a number of reasons. For example, it establishes a lower limit to the sensitivity of an infrared cell. We developed a theory for the noise spectrum which clearly indicates the direction in which to go in developing more sensitive cells. Furthermore, this theory enables us to evaluate a variety of basic characteristics of the semiconductor, as well as to predict the noise behavior of other semiconductor devices such as diodes and transistors.

We are currently conducting fundamental studies of the energy band structure in these compounds through the techniques of magnetoresistance and piezoresistance studies.

Our optical absorption edge data indicates very nearly the same energies for direct and indirect transitions. This, coupled with the magnetoresistance data, suggests that at least for PbTe, the energy surfaces are ellipsoids oriented along the 111 axis and that the extrema of the conductor and valence bands are near the same values of the momentum vector. Our data are not sufficiently precise to comment on the corresponding factor for PbS and PbSe.

A recent advance in the materials preparation work at NOL, White Oak, is the development of a technique for pulling single crystals of a volatile compound such as PbTe from the melt. These crystals have a more perfect structure than those obtained by the Bridgman technique and will make possible more precise studies of the properties of these semiconductors.

Current investigations include studies of the thermoelectric power of PbTe crystals, grown by the pulling technique. This work will shed light on the effective masses and electron-phonon interactions at low temperatures. Evidence of phonon drag effects upon the thermoelectric power has been found in the purest PbTe crystal at liquid-nitrogen temperature.

We have also studied the chemical kinetics of the process for depositing photoconductive films of PbS from solutions. This work has an important bearing on the commercial process used for this purpose.

The program on InAs resembles the lead-salt work in that the materials problem had to be worked out first. A similarly comprehensive study of the fundamental physics of this material is being made. We have established some of the features of the energy band edges in InAs and are currently studying the lifetimes, optical absorption, mobility, etc., of single crystals. One of the practical uses of this information was the development of an interference filter for an infrared device now in production.

To summarize: The effective combination of the disciplines of physics, chemistry, and metallurgy have helped us in NOL to clarify many of the problems that existed in the lead-salt semiconductors and have advanced our understanding of how to deal with nonstoichiometric semiconducting compounds.

The research program at NOL, Corona, is relatively new and is related to the problem of interference filters for use in the infrared. The problems of producing films having the same dielectric constant properties of bulk materials are being studied. The major work at this laboratory is more of a testing and evaluation of photoconductive cells.

Through the efforts of these three Navy laboratories our Defense Department is being kept in the forefront of the basic knowledge of materials which are useful in some of its infrared applications. Some of this work has already resulted in devices useful to the Navy's mission.

BRITTLE FRACTURE

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ABSTRACT

Brittle fracture may be defined either in terms of the mechanics of the situation, or in terms of the appearance of the fracture. To forestall service failures we must understand those that have already occurred, but the information recoverable through investigations of service failures is not sufficient. Therefore, we study relatively simple model fracture situations in the laboratory – fracture tests. There is a wide variety of these; we aim here to indicate a connection between the basic fracture mechanics approach and three of the transition temperature concepts – the Nil-Ductility Temperature, the Fracture Transition for Elastic Loading, and the Full-Shear Temperature.

Using classical stress analysis, with certain simplifying assumptions, we can characterize the stress field intensity around the edge of a crack by a single parameter, K. We then postulate a property of the material K_c, dependent upon degree of constraint and temperature, such that crack propagation will become unstable whenever K reaches the value K_c. To determine K_c for a material we use a test so designed that the value of K at the point of unstable fracture is readily calculable.

We define another quantity, $\beta_R = K_c^2/(B\sigma_{dy}^2)$, as a measure of the ratio of the size of the plastic zone around the tip of a propagating crack to the plate thickness B. When β_R is large the fracture mode will be oblique shear; when it is small the fracture will be brittle. For high-strength materials, with inappreciable dynamic elevation of the yield strength, β_R needs to be about 6 or more in order that nominal stresses equal to the yield strength can be sustained safely. This corresponds to 80- to 100-percent shear fracture and can, thus, be interpreted as meaning that the service temperature should exceed the Full-Shear Temperature. For mild steel, with about 150-percent dynamic elevation of the yield strength, β_R needs to be only about 0.5 in order that nominal stresses equal to the static yield strength can be sustained. This is believed to correspond to the Fracture Transition for Elastic Loading (FTE).

* * * * *

INTRODUCTION

Brittle fracture of an engineering structure can be regarded in two ways: (a) as fracture which occurs under loads considerably less than would be required for failure of the structure by plastic distortion and (b) as fracture which has a characteristically "brittle" appearance. The purpose of this article is to discuss the connection between these two viewpoints, as reflected in certain methods of fracture testing, in relation to the concepts of fracture mechanics.

Since the well-known instances of brittle fracture of liberty ships and tankers in World War II, there have been brittle-fracture failures of fuselages, canopies and landing-gear members of aircraft, storage tanks, pipelines, turbine rotors, extrusion presses, reactor pressure vessels, and casings and other components of rockets. Navy scientists have studied many such examples of brittle-fracture service failures. While much can be learned from such studies, the information recoverable is often insufficient by itself to suggest how further failures might be avoided – the magnitudes of the stresses, nature of the primary fracture origin, and the material properties are often not ascertainable.

For this reason the study of simple-model fracture situations in the laboratory has been extensively pursued, that is to say, there has been a lot of what is called fracture testing. A wide variety of brittle-fracture tests have been designed and used, as illustrated by Table 1. This table includes most of those tests which utilize a specimen having a notch or an artificial crack as an essential feature and is intended to be illustrative, not comprehensive. Discussions of brittle-fracture tests are to be found in Refs. 1 to 5.

There are three points to be made here with reference to Table 1. Firstly, there is widespread agreement that a sensitive brittle-fracture test, suitable for structural materials, requires a specimen incorporating a stress-concentrator in the form of a notch or, alternatively, an artificially introduced crack.

Secondly, the influence of size effects on fracturing must not be neglected. Results of tests of small specimens cannot safely be applied to structures of heavier section until a reliable correlation basis has been established by experiment. Docherty was one of the earlier workers to recognize this and to study heavy sections by notched bend testing. Fracture studies at the U.S. Naval Research Laboratory, which began with Docherty-type tests in 1942, have consistently emphasized dimensional effects. For example, Fig. 1 shows the wide range of specimen sizes which have been used in the Drop-Weight Test (5).

Thirdly, three major themes are discernible among the items in the table: fracture toughness in terms of load-bearing capacity, fracture toughness in terms of fracture appearance, and fracture toughness as influenced by temperature. The relationship between these will now be considered, using for illustration the basic fracture mechanics concepts of the fracture toughness parameter, K_c (1,6) and three transition temperature concepts related to appearance aspects – the Full-Shear Temperature, the Fracture Transition Temperature (Elastic), and the Nil-Ductility Temperature (2).

THE MECHANICS OF FRACTURE

The fracture mechanics approach is to apply the methods of classical stress analysis to study the elastic stress field close to the leading edge of a crack in a structure under load (1,6). With certain simplifying assumptions it can be shown that this stress field can be characterized, for the present purpose, by a single stress-intensity parameter, K. K has the general form of the product of the nominal tensile stress component normal to the crack with a factor which takes account of crack size and of the significant dimensions of the structure. The derivation of K

Table 1
Types of Notched-Specimen Brittle-Fracture Tests

Specimen Features	Test Features	Test Objectives	Used by (representative only)
Notched Beam Type			
1. Small	Pendulum Impact (also slow bend)	Transition Temperatures (energy ductility, fracture appearance)	Charpy, Izod, Mesnager, Schnadt, and numerous others
2. Small (sheet)	Pendulum Impact	Energy to Fracture	Arnold, Hartbower, Orner
3. Full Section Thickness and Smaller	Slow Bend	Energy to Fracture	Docherty
4. Full Section Thickness and Smaller	Slow Bend	Fracture Toughness dW/dA	Trimble, H. L. Smith
5. Full Section Thickness and Smaller	Slow Bend	Notch Strain, Strain Energy, K_c	Lubahn
6. Full Section Thickness and Smaller (crack)	Drop Weight Impact	Transition Temperature (nil ductility)	Pellini, Puzak, Babecki, Eschbacher
Notched Tensile Type			
7. Symmetric, Notched, Round	Slow	Notch Strength, Notch Ductility, Energy	Kuntze, Sachs, McAdam, Orowan, and numerous others
8. Symmetric, Notched, Round	Impact	Fracture Toughness, K_c	Yukawa, Carman, Krafft
9. Symmetric, Edge-Notched Rectangular Bar	Slow	Fracture Mode and Appearance	Tipper
10. Symmetric, Edge-Notched Plate	Slow	Fracture Stress, Appearance, Deformation	Parker, Vanderbeck, Gensamer, and many others
11. Symmetric, Edge-Cracked Plate	Slow	Fracture Stress, Appearance, K_c	Wessel
12. Symmetric, Edge-Cracked Plate	Slow	Transition Temperature	A. A. Wells
13. Symmetric, Small, Edge-Notched Sheet (high strength)	Slow	Notch Strength, K_c	W. F. Brown, Sessler
14. Symmetric, Center-Notched Plate (and sheet)	Slow	Fracture Toughness, K_c	Irwin, Kies, Romine, Bernstein, Gilbert Hodge, Frisch
15. Symmetric, Small, Center-Cracked Sheet (high strength)	Slow	Transition Temperature (full shear) Fracture Stress, K_c	Srawley, Beachem, Marshall
16. Asymmetric, Edge-Notched Plate	Slow	Energy to Fracture	Kahn
17. Asymmetric, Edge-Cracked Plate	Constant Load, Impact Trigger	Transition Temperature for Fracture Arrest	Robertson, Feely
Notch Bulge Type			
18. Plate, Crack-Starter	Explosive Shock	Transition Temperatures (NDT, FTE, FTP)	Pellini, Puzak, Babecki, Robertson
19. Sheet, Crack-Starter	Drop-Weight, Rubber Pad	Transition Temperature (fracture appearance)	Puzak, Pellini, Stoop
Notch Spin Disk			
20. Large, Notched Bore	Accelerate to Fracture	Fracture Toughness, K_c, Temperature Influence	Winne and Wundt

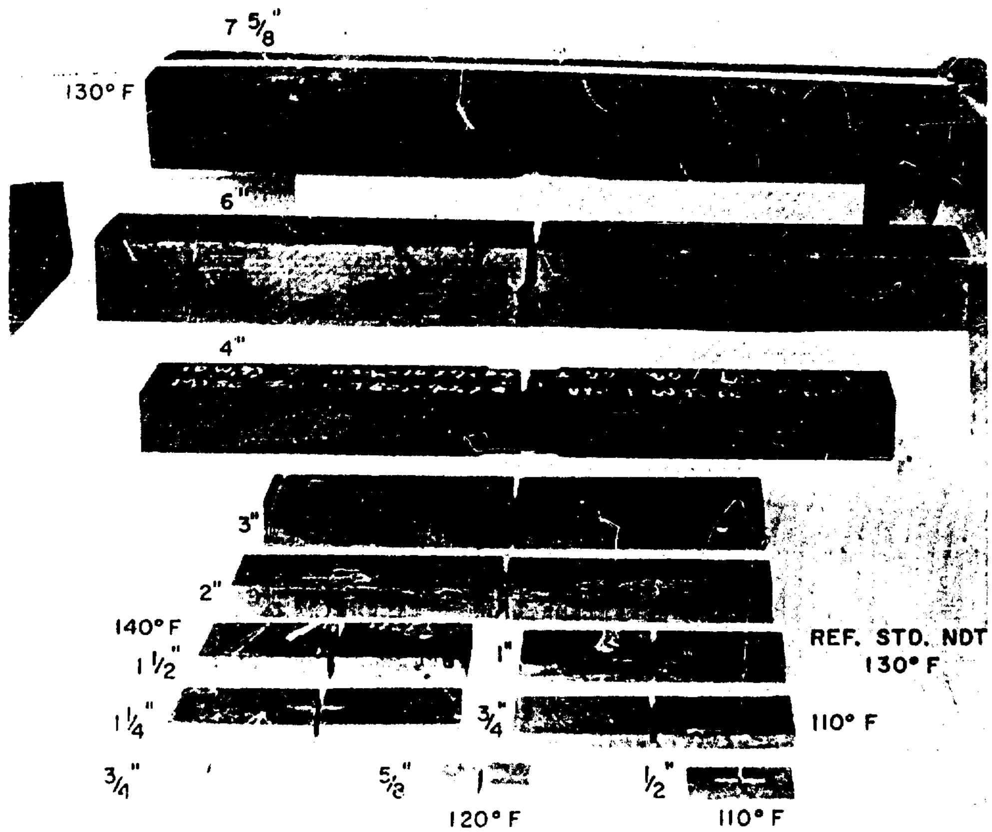

Fig. 1 - Range of size of NRL Drop-Weight Test specimens

for various simple general cases has been discussed in a number of publications (1,6) (in the earlier publications it is another quantity, $\mathcal{G}$, that is derived; this is identical with K^2 divided by Young's modulus).

Figure 2 illustrates the relationship between K, the stress, and the crack length for the simple case of an infinite plate of an ideal brittle material. The equation is $K = \sigma\sqrt{\pi a}$ in this case, $2a$ being the crack length and σ the nominal, uniform stress remote from, and normal to, the crack. For a given value of the crack length, K is proportional to σ. As the crack length increases, the ratio of K to σ increases.

K is not a stress concentration factor in the usual sense. However, it is a measure of the local stress elevation due to the crack. The particular K value necessary for unstable crack propagation in a given case is termed K_c, and it is essentially a materials property although it depends also upon the degree of constraint (e.g., the thickness of a plate) and upon temperature. Assuming that the horizontal dashed line in Fig. 2 represents the value of K_c for a given sheet of metal, then it is clear that rapid propagation will initiate at a high stress from a relatively short crack, or at a lower stress if the crack is longer.

In Fig. 3 the full line shows fracture stress values as a function of crack length replotted from Fig. 2. When the crack length is short enough, the predicted fracture stress will be

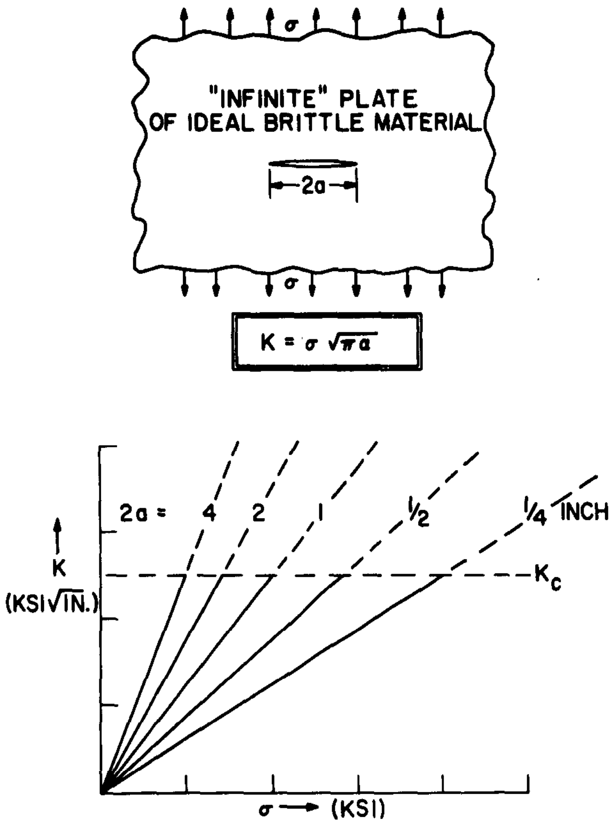

Fig. 2 - Stress intensity parameter, K, as a function of nominal stress normal to the crack and of crack length for a thin, "infinite" plate of an ideally brittle material

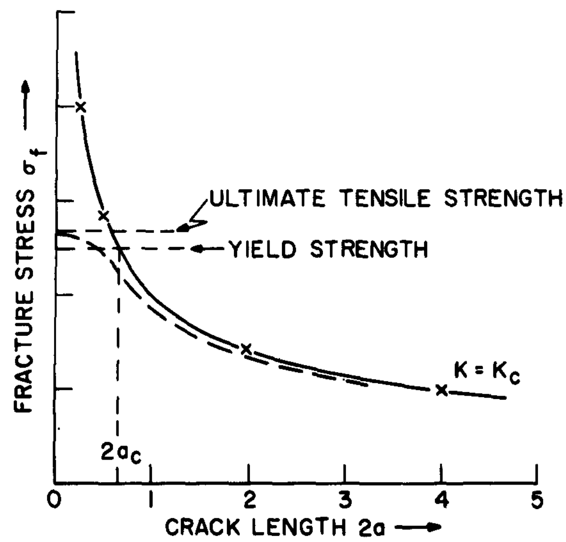

Fig. 3 - Relationship between expected fracture stress and crack length for an ideally brittle material of fracture toughness K_c (solid line) and for a real material (dashed line)

greater than the yield strength, and the plate or sheet is subject to failure before unstable crack propagation. For this idealized material there would be a minimum crack length, shown as $2a_c$, for brittle fracture.

The dashed line to the left of the full line represents what is actually found in tests of a real material. The deviation from the ideal curve is due to localized plastic distortion around the front of the crack. In the stress field analysis this is regarded as equivalent to an increment in the crack length proportional to the extent of the plastically strained zone. An appropriate correction for this is used in calculations of K and K_c so that the fracture mechanics analysis retains a useful degree of validity in the entire range of fracture stress values up to the yield stress.

A test procedure for K_c measurements must permit determination of K for the onset of crack propagation. Usually, the specimen design is such that a simple relation exists between K and the load and crack size. The test procedure then determines the critical values of load and crack size necessary for calculation of K_c. For example, simple rectangular sheet-tensile specimens, either centrally notched or edge notched, may be used for measurements of K_c on high-strength sheet materials as discussed in detail in Ref. 1.

FRACTURE CRITERION AND PLATE THICKNESS

This brings us to the point of a criterion of safety against brittle fracture. It would appear reasonable to suggest that a structure might be considered safe in this respect if the maximum nominal tensile stress could be brought up at least to the yield strength without risk of brittle fracture. To allow the stress to exceed the yield strength would presumably result in failure by plastic distortion. Knowledge of the fracture toughness K_c permits formal calculation of the critical crack length $2a_c$ corresponding to the yield stress. However, this is not as directly useful as one might hope in terms of flaw inspection of actual structures. The critical crack propagation length is $2a_c$, but a crack of this size might develop gradually in service from a smaller origin. The various ways in which this starting crack size can develop, for instance, low-cycle fatigue, are a subject of current research.

To meet this difficulty we turn to something which has been learned from examination of many fractures of high-strength, thin-walled pressure vessels. Characteristically, such fractures did not originate from prior through-cracks. Instead, the starting crack developed gradually by crack extension through the plate thickness from a flawed region (sometimes a prior crack) near one surface. Assuming that inspection procedures will limit such flaws to a small size, the resulting through-crack should not exceed a length equal to twice the plate thickness. It seems prudent to require that a plate should possess sufficient toughness to arrest propagation of such a crack if it forms. From this consideration we conclude that K_c for the material should be at least large enough to prevent the propagation of a crack extending through the thickness of the plate and equal in length to twice the thickness, when the nominal stress normal to the crack is equal to the yield strength.

At this point it is convenient to introduce another quantity, β, which is a measure of the ratio of the size of the plastic zone around the front of a crack to the plate thickness. By definition

$$\beta = \frac{K^2}{B\sigma_{ty}^2} \tag{1}$$

where B is the plate thickness and σ_{ty} is the tensile yield strength.

For unstable crack propagation β must be equal to (or greater than) a critical value β_R corresponding to $K = K_c$. Also, the dynamic-tensile yield strength σ_{dy}, corresponding to the strain rate at the rapidly moving crack front, must replace the static yield strength; hence

$$\beta_R = \frac{K_c^2}{B\sigma_{dy}^2}. \tag{2}$$

For the case of an "infinite" plate we make use of the formula incorporating the plastic zone correction, instead of the simpler formula of Fig. 2, namely,

$$K_c^2 = \frac{\pi a \sigma^2}{1 - \frac{1}{2}\left(\frac{\sigma}{\sigma_{dy}}\right)^2}. \tag{3}$$

Substituting for K_c in Eq. (2),

$$\beta_R = \frac{\pi a \sigma^2}{B\left(\sigma_{dy}^2 - \frac{1}{2}\sigma^2\right)}. \tag{4}$$

Applying the suggested requirement that the nominal stress for unstable crack propagation should be not less than the (static) yield strength when $a = B$, i.e., $\sigma = \sigma_{ty}$, we obtain a minimum required value of β_R

$$[\beta_R]_{Minimum} = \frac{\pi}{\left(\frac{\sigma_{dy}}{\sigma_{ty}}\right)^2 - \frac{1}{2}}. \tag{5}$$

Thus, the minimum required value of β_R should depend solely on the ratio of the dynamic to the static yield strengths. The connection between this and the fracture appearance will now be illustrated by examples.

FRACTURE APPEARANCE AND TESTING TEMPERATURE

The very-high-strength sheet steels used for construction of large solid-propellant rocket motor casings will be considered first. Commonly, these materials are used at yield strengths of 200 ksi and above. It has been shown that there is very little dynamic elevation of the yield strength for these steels, and accordingly the dynamic yield ratio may be taken as unity. The required β_R value from Eq. (5) is therefore equal to 2π.

Typical fractures of such steels are shown at the right-hand side of Fig. 4. The appearance of the fracture may vary from the transverse "brittle" type, which exhibits chevron markings when examined directly, shown at the bottom, to the entirely oblique "shear" type shown at the top, with intermediate types in which a central band of transverse fracture is surrounded by oblique "shear" borders. It is convenient to use the percentage of the thickness of the specimen occupied by the shear borders as a measure of fracture appearance – referred to as the "percent shear" (7,8). For a given material in a given condition and at a particular temperature, the percent shear will be less the thicker the material. For a particular thickness the percent shear will increase with increasing testing temperature until the fracture becomes entirely shear (except for a small triangular area at the origin) at some minimum temperature,

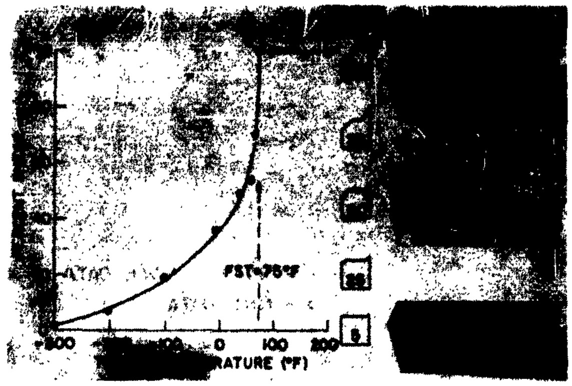

Fig. 4 - Percent-shear fracture border as a function of temperature for a high-strength, low-alloy steel sheet. The Full-Shear Temperature is 75°F.

which is referred to as the Full-Shear Temperature (FST). The plot in Fig. 4 shows the variation of percent shear with testing temperature for a proprietary low-alloy steel sheet for which the FST is sharply defined.

Figure 5 is a plot of percent shear versus the value of β at the onset of unstable fracturing for a variety of high-strength sheet materials, all tested at room temperature. In spite of the scatter there is a strong indication of a correspondence between the range 80- to 100-percent shear and values of β equal to 6 or more. Thus, there is support from fracture mechanics concepts for the suggestion that a desirable high-strength sheet material should have a Full-Shear Temperature lower than the lowest anticipated service temperature (7,8). This is reinforced by the knowledge that the fracture toughness K_c decreases at temperatures below the FST in a manner similar to the percent shear and is thus very sensitive to small temperature changes in this range.

It is also important to note that the FST for a given material depends strongly upon the sheet thickness. Figure 6 is an example of this dependence for a steel which is widely used in rocket casing construction – a selection which is endorsed by the fact that the FST values are well below room temperature.

Fracture appearance observations and measurements are of particular value because in some cases they may be the only means of relating a service failure to laboratory testing. They may also serve as a useful check on the reliability of a fracture toughness measurement in cases where the specimen is narrow, or the initiating notch of doubtful sharpness. In addition, they are of value in research on material factors where increased understanding of fracturing may result from comparison of fracture topography with microstructure. On the other hand, it should be emphasized that there are high-strength materials which have relatively low fracture toughness even at temperatures above the FST. Some high-strength titanium alloys are of this type. It follows that having an FST below the lowest service temperature cannot be regarded as a sufficient criterion, in itself, of the suitability of a material. It must be combined with a satisfactory fracture toughness based upon a load-bearing capacity measurement.

The second example to be considered is mild steel, e.g., ship plate. It has been shown by Baron (9) that the dynamic yield strength at a strain rate of 200 per second is about 2.5 times the static yield strength for this material. Using this ratio in Eq. (5), the required value of β_R is about 0.5, which corresponds to a very low value of the percent shear, probably less than

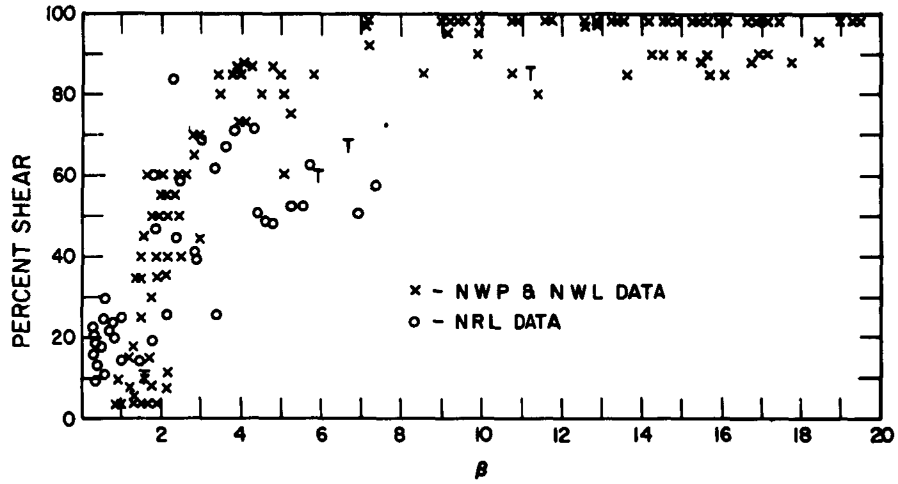

Fig. 5 - Percent-shear values plotted against corresponding values of the parameter β at fracture for a variety of high-strength sheet materials, all tested at room temperature

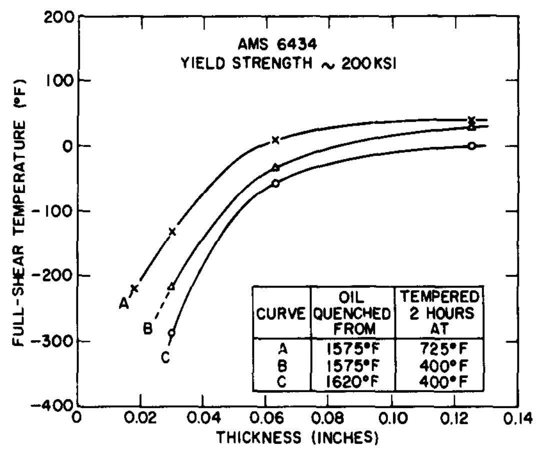

Fig. 6 - Dependence of Full-Shear Temperature on sheet thickness for AMS 6434 rocket casing steel. All thicknesses were rolled from the same heat of steel.

5 percent. Figure 7 shows the appearance of Explosion Bulge Test Specimens of 1-inch-thick ship plate related to Charpy test results (10). In the lower right-hand corner there is a plot of shear border width which shows that the Fracture-Transition-Elastic (FTE) corresponds to the range 2- to 4-percent shear, whereas the Nil-Ductility-Transition (NDT) corresponds to almost zero-percent shear. Thus, the criterion of toughness sufficient to arrest a crack twice the plate thickness in length is more conservative than the NDT for ship plate, and probably corresponds more nearly to the FTE. (The established criterion for the NDT is whether or not the test plate is slightly permanently bulged by the shock wave before it shatters; that for the FTE is whether or not the cracks propagate all the way to the edges of the plate so that it breaks into pieces.) The fact that the NDT has been found to correlate well with service fracture temperatures of ships (5) indicates that the fracture toughness criterion may be overly conservative for ordinary ship service. This simply reflects the fact that under normal

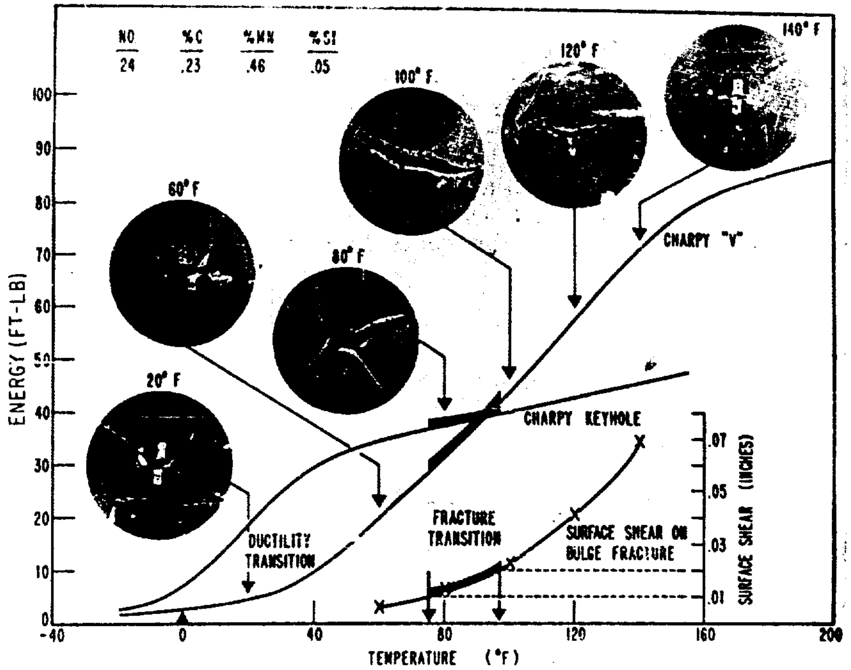

Fig. 7 - Shear border widths of Explosion Bulge Test specimens as a function of temperature of testing (lower right-hand corner) related to Fracture-Transition-Elastic temperature range

circumstances the nominal stresses in a ship are not expected to reach a level anywhere near the yield strength. For collision conditions the FTE is regarded as the appropriate criterion, and it appears that this may correspond quite well with the fracture toughness criterion.

CONCLUSION

It is obviously desirable, wherever possible, to be able to predict brittle fracture by calculations involving the expected loads, the configuration of the structure, and pertinent material properties. The only promising approach known to the authors is through the concepts of fracture mechanics which have been outlined. This approach is essentially concerned with local intensification of the stress field in the vicinity of flaws, such as cracks. In the absence of flaws of significant size, there would seem to be no reason for fracture to occur prior to widespread deformation.

Calculations of critical crack lengths are complicated by the phenomena of slow growth of cracks, a subject not yet well understood. Pending further developments in this direction, critical crack lengths must be regarded with caution. However, the minimum-toughness requirement related to the plate thickness, which has been discussed, offers a rational and useful basis for comparison of materials and for interrelating different fracture testing procedures.

In dealing with thin-walled structures, both temperature and thickness have important effects which are interrelated through the mode of fracture. The practical usefulness of transition-temperature concepts arises out of this, and it is evidently of interest to understand as far as possible the complex relationships between transition-temperatures and mechanical-fracture toughness measures. Our understanding of brittle fracture has not yet developed to the point where we are able to show an exact correspondence between transition-temperature criteria and mechanical-fracture toughness criteria; however, it has been possible to show an approximate correspondence for two widely different classes of material: very-high-strength sheet steels, and low-strength ship plate steels. For the former, the Full-Shear Temperature corresponds, in general, with the fracture mechanics minimum β criterion, while for the latter the Fracture-Transition-Elastic seems to be the appropriate temperature and is associated with about 2- to 4-percent shear border. For an intermediate case, such as a rotor forging steel, we would expect correspondence at an intermediate level, perhaps 50-percent shear.

Much remains to be learned about brittle fracture and significant fracture testing; nevertheless, steady progress is being made toward the ultimate goals of rational design of engineering structures against brittle fracture, and of rational criteria for the selection of materials which are of direct usefulness in the design procedures. The latter will presumably also provide the necessary connection between engineering fracture problems and the microstructures and submicrostructures of engineering alloys.

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IRRADIATION EFFECTS IN MAGNETIC MATERIALS

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* * * * *

ABSTRACT

Extensive investigations of the effects of nuclear enviroments upon magnetic materials have been undertaken. Information of interest to design engineers on the one hand, and to theoretical physicists on the other, have been obtained. Materials such as silicon-iron and some ferrites show no significant changes in magnetic properties at 60 cycles. Materials such as the permalloys are grossly affected by irradiation. The enhanced magnetic properties of these materials result from specific crystallographic arrangements obtained through combinations of thermal and mechanical treatment. Here it is clear that atomic displacements resulting from nuclear irradiation should produce significant changes in the magnetic properties of these materials. A detailed study of the mechanisms involved further suggests that in some materials these deleterious effects may be minimized or eliminated if the material is placed in a saturating magnetic field during the period of irradiation. This has been the case. Indeed in some materials it is actually possible to obtain better magnetic properties by this process. The Neél-Taniguchi theory of magnetic uniaxial anisotropy will be applied to explain the results.

* * * * *

INTRODUCTION

With the Navy's active participation in the nuclear age it is apropos to discuss the effects of nuclear radiation upon magnetic materials. In terms of effects upon devices it is possible to consider radiation as an enviroment and to characterize this enviroment by listing its components and their variations with time and position. Suffice to say that the nuclear enviroment to which we refer includes electromagnetic radiation (i.e., X-rays, gamma rays), fission fragments, and fast and slow neutrons. In nonmetallic materials, such as dielectrics, electromagnetic radiation will produce ionization effects. But in metals and alloys, which are already ionized, these effects are not expected. Impinging particles, such as fast neutrons, on the other hand may have sufficient energy to produce atomic displacements in metals and alloys. Consequently those properties strongly dependent on atomic arrangements will be affected by neutron irradiation.

From the Navy's point of view radiation enviroments may be provided by various sources. For example, shipboard and land-based reactors are a possibility. Here, however, it may be possible to design for adequate shielding to prevent serious deleterious effects. In the case of airborne power plants, however, shielding is accomplished only at an extreme cost in weight and space, and consequently electronic and magnetic devices may be expected to encounter nuclear environments. It is also necessary to consider nuclear environments created by nuclear explosions where very intense pulses of radiation are expected. Radar blackout is already a well-established consequence of certain types of nuclear explosions. Although the cosmic particles, X-rays, etc., of outer space are not expected to produce atomic displacements, and therefore alter structure-sensitive properties, nevertheless, space cannot be dismissed entirely from consideration, for nuclear-propelled vehicles are planned for distant outer space journeys. These nuclear-powered devices would carry their own reactors and therefore produce radiation enviroments which could bathe various components with nuclear particles. Furthermore, electronic devices used in the guidance, control, etc., of various missiles may be thrown out of commission by certain types of nuclear bursts.

At this point, it is possible to list the types of electronic equipment and components susceptible to radiation and to indicate the amount of information available. In the case of ordinary circuit elements where resistors, capacitors, and general hardware are lumped together, much data has been accumulated and is in the open literature. This is also true for semiconductor devices – diodes, transistors, etc. Two categories of components of extreme interest to the Navy are transducers and magnetic devices. But very little data exists on irradiation effects in transducers, while intensive work on magnetic materials has been conducted only within the last two years, and largely by the Navy (1).

Figure 1 shows the radiation sensitivity of various classes of materials, rather than of specific items of hardware. The figure shows the total dose of fast or high-energy neutrons which specific classes of materials may tolerate before significant damage occurs, i.e., before, say, a 10-percent alteration occurs in an important property of the material in question. The ordinate scale refers to the total dosage or total number of neutrons striking per square centimeter of material. The sensitivity value for magnetic materials is slightly above that at which organic liquids, such as transformer oils, deteriorate but below the dosage which produces structural changes in metals and alloys. The number 10^{17} nvt corresponds to an exposure for a fracture of a second to a nuclear explosion of present size or to an exposure for a week or two to direct beams from conventional reactors.

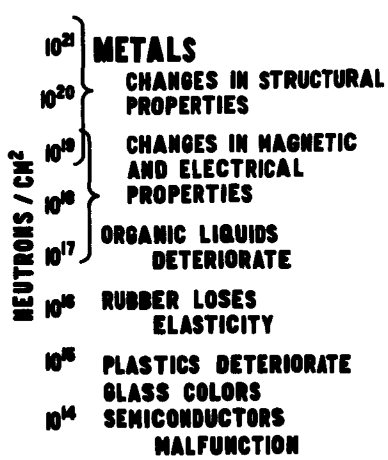

Fig. 1 - Sensitivity of materials to pile radiation

The magnetic hysteresis loop is very useful in studies of changes in magnetic properties due to irradiation because it shows the relationship between the externally applied magnetic field and the magnetization induced in the sample. Starting with a material which was magnetically saturated, and removing the applied field, one finds a residual magnetism B_R. To reduce the induced magnetization to zero a field must be applied in the negative direction. The value of the applied field which gives a zero induction is called the coercive force, H_c. The shape of the hysteresis loop and these two parameters are strongly dependent on the atomic arrangement of many of the alloys to be discussed. Specific applications of magnetic devices depend upon the shape of the hysteresis loop of the magnetic materials used. For example, consider the rectangular loop necessary for satisfactory operation of the memory-storage devices in computers. Various components in the computer operate on the assumption that the storage device does have a rectangular loop with relatively sharp corners. If the hysteresis loops would be altered these devices would then malfunction.

EXPERIMENTAL RESULTS

The irradiation and measurement procedures used in the experiments described here are similar to those previously described (1). Suffice to say that sixty-cycle loops were obtained on toroid samples of various magnetic alloys before and after irradiation. All measurements were made in the NRL hot cell using the same circuitry. The samples were irradiated in the Brookhaven graphite reactor which operated between 15 and 22 megawatts during the various exposures. The total integrated flux received by the samples varied between 6×10^{16} and 3×10^{17} nvt. By means of forced cooling the temperatures of all samples were kept below 75°C, and some as low as 30°C.

As indicated in Ref. 1, certain materials were found to be insensitive to radiation with respect to their 60-cycle characteristics and, therefore, would not require shielding. These materials included silicon steel and similar alloys (Fig. 2) and many types of commercial ferrites (mixed iron oxides). These alloys are also relatively stable to mechanical and thermal treatment. Unfortunately, they do not have very exciting magnetic properties and are not used in sophisticated electronic and magnetic devices.

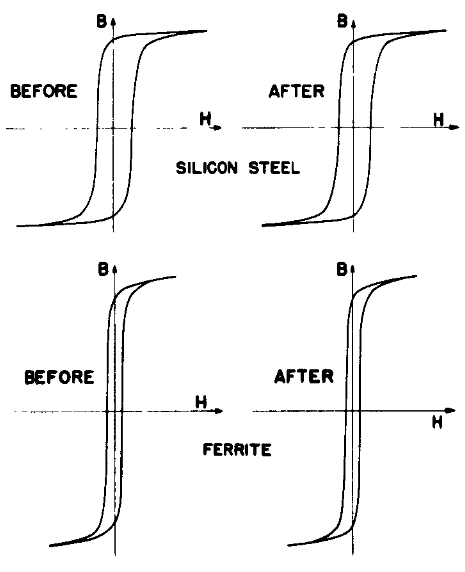

Fig. 2 - Example of a radiation insensitive alloy (silicon steel) and a radiation insensitive ferrite. The loops on the left were obtained before irradiation; the loops on the right were obtained after irradiation.

On the other hand it was also shown that a large class of alloys are grossly affected (Figs. 3 and 4). In some cases not only are the remanence and coercive forces altered, but constrictions are introduced in the hysteresis loop itself. The practical significance of these changes may be inferred from Fig. 5. In the upper left corner is an ideal hysteresis loop for a memory storage device which might be used in an airborne computer, for example. The hysteresis loop is rectangular with sharp corners. The feed-out pulse from a device with such a loop would in turn be rectangular and have sharp corners as shown below (or to be more exact, the pulse would have the shape of a delta function). The more conventional loop is shown in the middle with the corresponding bell-shaped feed-out pulse. But if a constriction is introduced into the hysteresis loop, as in the upper right-hand corner, the feed-out pulse has two peaks, and certainly a device whose operation is predicated on receiving only sharp single-peaked responses would grossly malfunction.

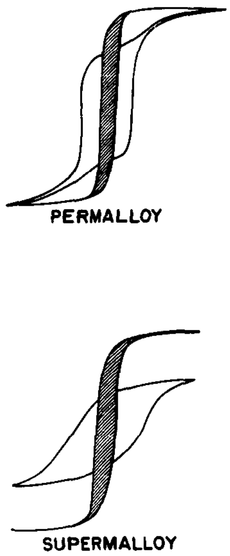

Fig. 3 - Examples of alloys grossly sensitive to radiation. The cross-hatched loops were obtained before irradiation, the open loops after irradiation. Note that in the case of supermalloy, the alloy did not reach saturation after irradiation.

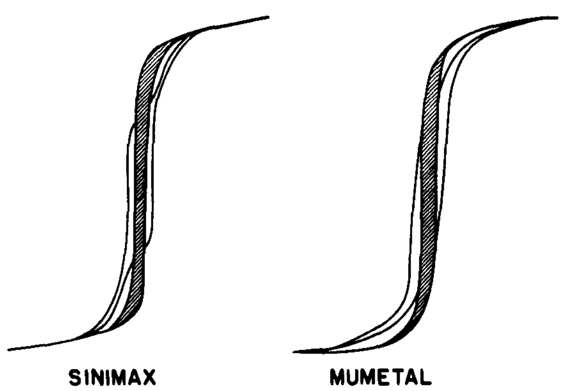

Fig. 4 - Additional examples of alloys grossly sensitive to radiation. The cross-hatched loops were obtained after irradiation.

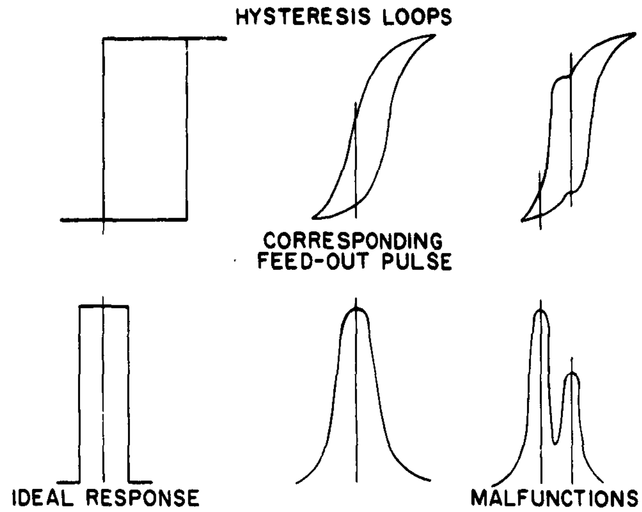

Fig. 5 - Examples of three types of hysteresis loops of materials to be used in magnetic devices. Lower set of curves indicate nature of feedout pulse resulting from each type of loop.

It may be stated categorically that those alloys whose magnetic properties show significant sensitivity to nuclear irradiation are the materials which originally have been given enhanced magnetic properties through special combined mechanical and thermal treatment, i.e., the permalloy treatment. Although a detailed understanding of the mechanisms involved in the permalloy treatment is not available, atomistically the treatment arranges the nickel and iron atoms into some sort of nearly regular arrangement or order. Consequently, atomic displacements produced by impinging neutrons can cause the degree of order to be altered considerably, and those magnetic properties sensitive to atomic arrangement are altered. Within recent years, Kaya (2) and others have shown a correlation between the shape of the hysteresis loop and the degree of order in permalloys. Schindler, Salkovitz, and Ansell (3) have given a variety of heat treatments to various types of 50-50 and 75-25 nickel-iron alloys in the form of tape-wound toroids. These treatments brought each sample to some particular state of order, and for each sample characteristic hysteresis loops were obtained. Each sample was then irradiated and the new loops recorded. The nature of resulting changes in the loops (Fig. 6) were found to be dependent on the nature of the loop of the preirradiated sample and, therefore, the degree of order in the original sample. The constricted loop in the lower right corner is characteristic of partially ordered material. A material which orders more readily is supermalloy (75% Ni - 25% Fe). Schindler, Salkovitz, and Ansell were able to show that with irradiation a higher degree of order could be obtained than with a given thermal treatment. The results of this paper confirmed work by others (4), that the degree of order may be altered not only thermally but also by irradiation and that the two processes are additive.

At this point it is germane to discuss theories which have been developed in the last few years to explain magnetic annealing in alloys. Consider an unordered solid solution of atoms A and B as in Fig. 7(a) where the solid circles represent A-atoms and the open circles represent B-atoms. For ideal random arrangement 28 pairs of each type of atom are expected, and 56 mixed. In fact there are 29AA, 29BB, and 54AB pairs. For perfect order no like-atom pairs are expected, as in Fig. 7(b). But, there is a third example to consider as shown in Fig. 7(c). Here, there are 29 pairs of AA, but 20 are in the vertical direction, and 9 are horizontal. This is not order in the usual crystallographic sense. Yet it shows a definite directionality as a result of preferential alignment of like-atom pairs. On such a model Neél and Taniguchi (5) independently proposed an explanation for the uniaxial magnetic anisotropy that occurs in binary alloy annealed in a magnetic field.

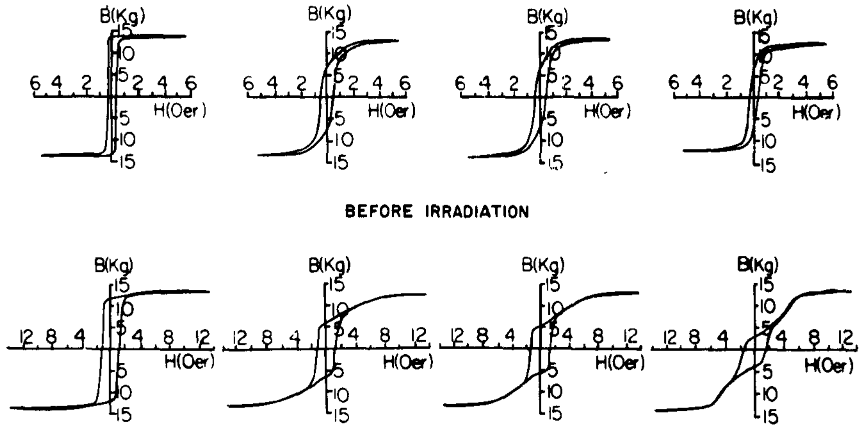

Fig. 6 - Four samples of Deltamax (50% Ni - 50% Fe) thermally treated. Arranged left to right according to increasing degree of order.

If the normal magnetic anisotropy is small, as in the case of permalloys, then any additional uniaxial anisotropy has a strong effect on the magnetization process. The direction of the uniaxial anisotropy that is created by annealing in a magnetic field is the same for all of the magnetic domains and this results in a square hysteresis loop. Annealing in the absence of a magnetic field also causes uniaxial anisotropy, but the direction of the anisotropy will be different from domain to domain, and a constricted or kinked hysteresis loop will be obtained. An indirect method of examination of the growth of uniaxial anisotropy then consists of a study of the magnetic hysteresis loop. For iron-nickel alloys there is also a tendency for long-range superlattice formation, i.e., formation of Ni_3Fe. As the formation of the Ni_3Fe superlattice occurs, short-range directional ordering, and consequently uniaxial anisotropy, decreases and the more normal hysteresis loop is obtained. The new hysteresis loop will of course have different values of coercive force and remanence consistent with the values of cubic anisotropy and magnetostrictive constants of the ordered alloy.

With the above considerations in mind, Schindler and Salkovitz (6) carried out additional experiments in which the samples were irradiated in the presence of a saturating magnetic field. The samples used were commercially available toroids, mainly of iron and nickel alloys of the following compositions:

1. 4% Mo - 79% Ni - 17% Fe (permalloy)
2. 5% Mo - 79% Ni - 16% Fe
3. 5% Cu - 2% Cr - 78% Ni - 15% Fe (mumetal)
4. 48% Ni - 52% Fe

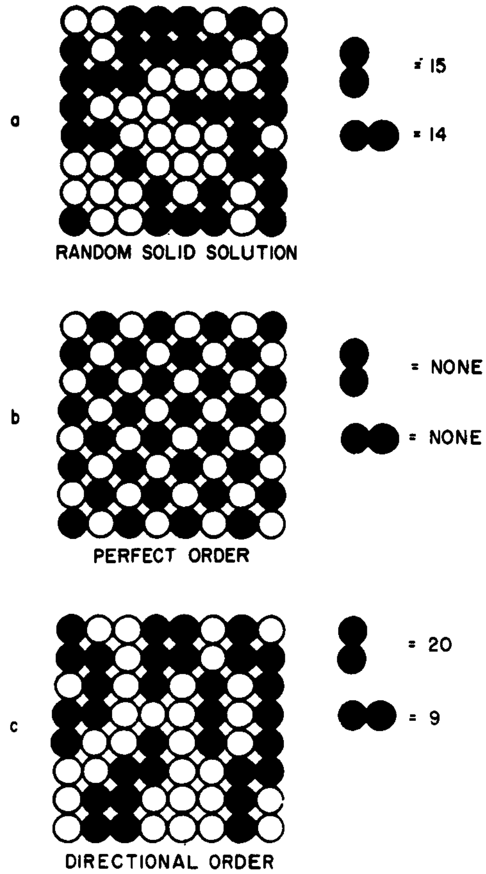

Fig. 7 - Two-dimensional array of a 50-50 alloy according to various types of order (Graham – Chapter 13, Magnetic Properties of Metals and Alloys, 1958)

Two samples of each material were wound with appropriate B and H coils and installed on the same sample holder. Preirradiation, 60-cycle, hysteresis-loop measurements were taken and the samples were then irradiated at the Brookhaven reactor for two weeks. This short irradiation time was chosen so that only short-range ordering could occur. The total integrated flux for these samples was

$$\phi \text{ fast} = 1.25 \times 10^{16} \text{ to } 3.0 \times 10^{16} \text{ nvt}$$

$$\phi \text{ epi} = 2.6 \times 10^{17} \text{ nvt}$$

$$\phi \text{ thermal} = 5.9 \times 10^{18} \text{ nvt},$$

while the temperature during irradiation was kept relatively constant, the limits being between 80°C and 120°C for the various samples. During irradiation a saturating magnetizing dc current was passed through the H coil of one sample of each pair. The field produced was in the same direction as the field applied during hysteresis-loop measurements. After the irradiation, the hysteresis loops of each sample were taken again.

Figures 8 and 9 show the preirradiation and postirradiation hysteresis loops of permalloy and mumetal. The preirradiation loops are marked (a), while the postirradiation loops are the curves marked (b) and (c). Loop (b) is the hysteresis loop of the sample irradiated in the absence of a magnetic field, while loop (c) is that for the sample irradiated in the presence of a saturating magnetic field applied to the toroid. In both cases, loop (b) is similar to results previously observed, i.e., decreased remanence, increased coercive force, and decreased permeability. (Note: to saturate the irradiated sample, a field several times that of the preirradiation saturing field was required.) In loop (c) a strikingly different effect was observed, namely, rectangular loop characteristics were obtained with both the coercive force and the remanence increasing.

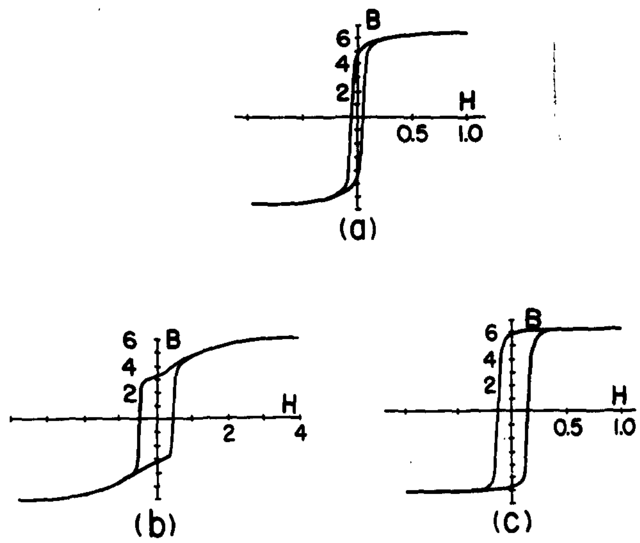

Fig. 8 - The effect of neutron irradiation on the 60-cycle hysteresis loops of permalloy: (a) preirradiation hysteresis loop; (b) post irradiation hysteresis loop - no field applied during irradiation; and (c) post irradiation loop - saturating magnetic field applied during irradiation

These results are consistent with the suggestions previously made that neutron irradiation causes ordering in Ni-Fe alloys. The modified hysteresis loops reflect a change in the unaxial anisotropy of the state of final order. In the case of samples irradiated for short times in the absence of an applied field, the resulting directional, short-range ordering causes constricted hysteresis loops, while for samples irradiated in a magnetic field the resulting directional ordering causes rectangular hysteresis loops. It would also appear, for the samples irradiated in the absence of a magnetic field, that long-term irradiation causes the formation of the Ni_3Fe superlattice. The directional short-range ordering and the resulting magnetic anisotropy then decrease and the normal-shaped hysteresis loop is obtained. These results are of great significance in the development of theories concerning the relationship between the degree of order, magnetic anneal, and resulting magnetic properties. In addition, it should be noted that improved materials have been obtained. To date, it is impossible to obtain 2 mil permalloy tape by any known combination of thermal and mechanical treatment which has the rectangular loop characteristics of this irradiated material.

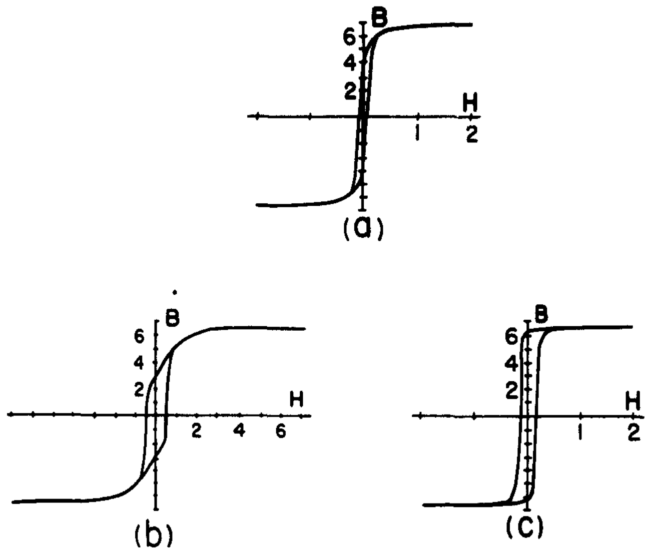

Fig. 9 - The effect of neutron irradiation on the 60-cycle hysteresis loops of mumetal: (a) pre-irradiation hysteresis loop; (b) post irradiation hysteresis loop – no field applied during irradiation; and (c) post irradiation loop – saturating magnetic field applied during irradiation

CONCLUSIONS

It has been demonstrated:

1. that there are magnetic materials which are radiation resistant. These materials do not have exciting magnetic properties or, conversely, they are stable to most treatments;

2. that alloys which do have enhanced magnetic properties, such as the permalloys, are very susceptible to irradiation;

3. that by making the detailed study of the phenomena, it has been possible to inhibit damage in some cases and, more important, to produce better magnetic materials;

4. that, finally, radiation studies may be used as a physical tool to study materials in magnetic states hitherto unobtainable in some of these materials.

ACKNOWLEDGMENT

The author wishes to acknowledge that the work described in this review has been conducted in collaboration with Dr. A. I. Schindler, and much of it directly by the latter.

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THERMOELECTRIC MATERIALS

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Bureau of Ships

The manuscript of this paper was not available for publication.

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METALLURGY IN THE NAVY. AIME-Navy Day Forum. 105 pp. and figs. February 15, 1960.

It is clear that every piece of military hardware is largely determined in its form, structure, and function by the contemporary state of the materials arts and sciences. The energy for the propulsion system of all our present military vehicles and weapons comes directly from the transformations of certain material compounds and elements into other material compounds and elements. The functionings of most of our present military payloads depend, at least in part, on the same sources of energy. The electrical, optical, thermal, chemical, biological, and structural properties of materials are all of detailed and vital significance in nearly every one of our defense devices.

There exists a strong feeling in many quarters that a substantial and important segment of the technical community remains poorly informed on these subjects. To alleviate this situation, the AIME-Navy
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